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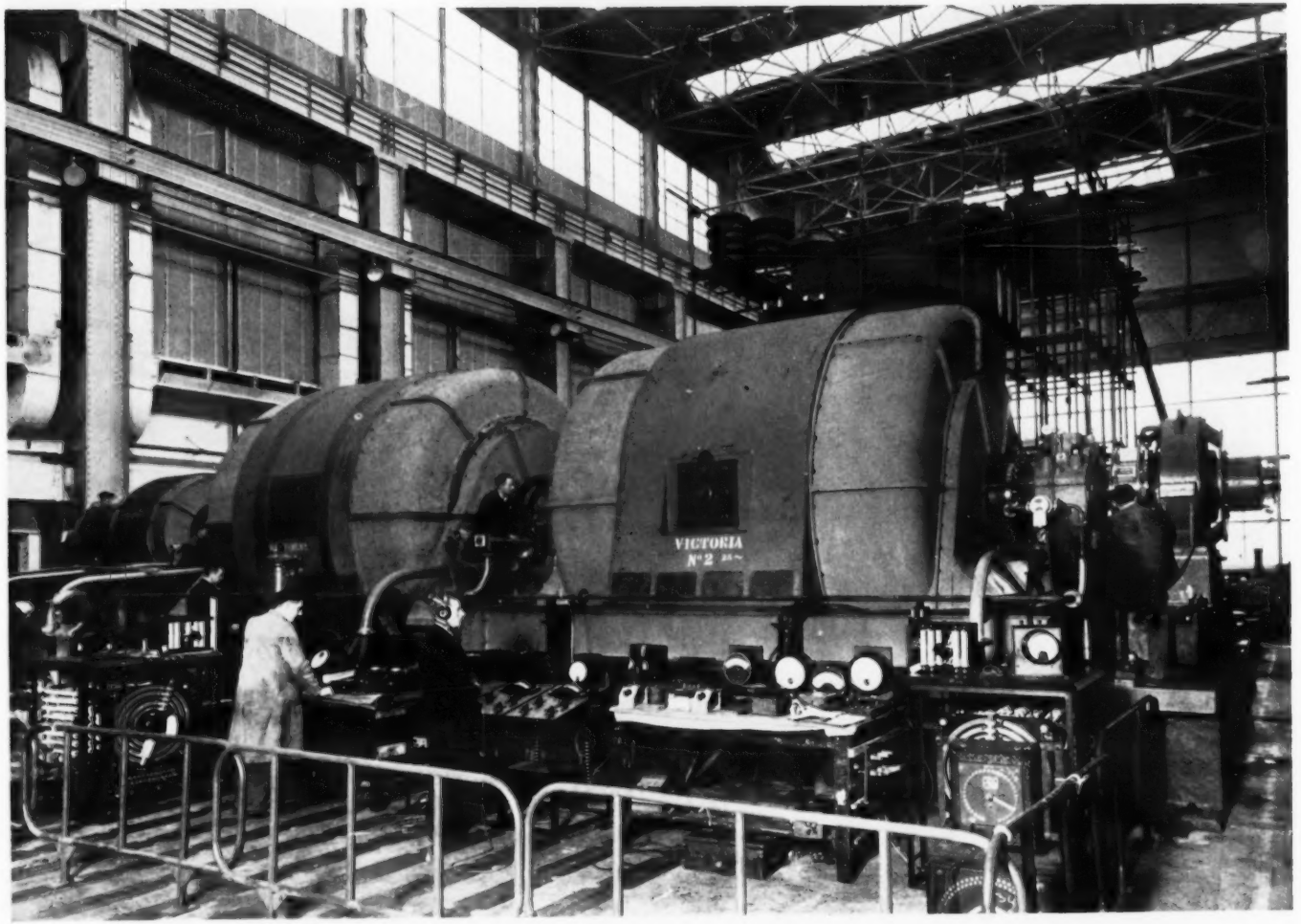


Running tests at the Stafford Works on the 30 MW 25/50 cycles frequency changer for the Newport Power Station of the State Electricity Commission of Victoria

A Frequency Changer for the State Electricity Commission of Victoria

By E. T. METCALF, B.Sc.(Eng.), A.C.G.I., A.M.I.E.E., Wh.Sc., Machine Design Department.

REPLACEMENT OF TWO of the original 25-cycle turbo-generators and associated boilers at the Newport ' A ' Power Station of the State Electricity Commission of Victoria, Australia, by plant of much higher rating, involved provision of reserve capacity to meet emergency and routine overhaul requirements. To take advantage of this reserve boiler and generating capacity when it is not actually needed for the 25-cycle load, it was decided to install a 30 MW 25/50-cycle frequency changer at the Newport ' B ' Power Station to supplement several much smaller units already linking the two systems at other stations, and so obtain some much needed relief for the overtaxed 50-cycle system. Another factor influencing the decision was the intended eventual changeover to rectifiers to supply the traction system, although this is not likely to have any marked effect for many years.

This frequency changer, which is believed to be one of the largest of its type in the world, was manufactured at the Stafford Works of The English Electric Company. It consists of the two main machines, the 25-cycle and 50-cycle 30 MW units, each of which is provided with a direct-coupled main and pilot exciter, together with an induction motor for starting, the overall length of the set being almost 63 feet. Each of the main machines has its own closed circuit ventilation system, with water-cooled air coolers, and the exciters and pony motor have open circuit ventilation.

Power may be transferred in either direction, *i.e.*, the 25-cycle and 50-cycle machines can both act as either generator or motor. When acting as generators, the maximum continuous ratings for temperature rises in accordance with B.S.226 are 30 MVA at 1.0 p.f. and 37.5 MVA at 0.8 p.f. for the 25-cycle and the 50-cycle machines respectively. Each, however, is capable of the somewhat higher rating necessary when acting as a motor.

Provision is made for rocking the stator of the 50-cycle machine through a total angle of 45 mechanical degrees, and for field reversal on both machines, to permit adjustment of phase before synchronising and of load after synchronising.

As it was desired to connect the set directly to the existing 25-cycle network without the use of a transformer, the 25-cycle machine had to be designed for the relatively high line to line voltage of 20 kV, while for the 50-cycle machine the voltage is even higher, namely 22 kV, although this is connected to a 66 kV system via a transformer.

The normal speed of the set is 750 r.p.m., but all rotating parts are designed to withstand an overspeed of 900 r.p.m. while still maintaining a reasonable factor of safety.

This combination of high output, speed and voltage, together with the need to rock the 50-cycle stator through such a large angle, presented a number of interesting problems in both design and manufacture.

General Arrangement

As shown in Fig. 1, the rotors of the two main machines are supported by three bearings which are of the pivoted pad type. Each machine is of the single pedestal bearing type, their shafts being coupled by a short shaft carried by the middle bearing.

The armatures of the main and pilot exciters for the 25-cycle machine are overhung from the outer bearing at the 25-cycle end, and their magnet frames are ' telescoped ' to keep the overall length of the set as small as possible.

The rotor of the pony motor is carried in its own

two bearings, and its shaft is flexibly coupled to that of the 50-cycle machine.

The armature of the main exciter for the 50-cycle machine is carried between the outer bearing of the pony motor and a further small bearing, from which the pilot exciter armature is overhung.

Transverse sections of the 50-cycle and 25-cycle units are shown in Fig. 2.

The set had to be installed at turbine floor level where previously there was an opening approximately 50 feet square, the basement floor being 22 feet below. The stator of the 25-cycle machine is therefore supported on a concrete block, designed to form a closed pit for the cooling air circuit, the coolers being mounted at the bottom. The 50-cycle stator frame, which is circular in form, rests on four pairs of rollers carried by a massive beam which together form the cradle of the rocking gear. This cradle is supported on a hollow concrete block designed to collect the air issuing from the underside of the stator frame and to lead it to the coolers below.

Construction of Main Machines

Stators

The frames are conventional in form, being of fabricated construction, with circular ribs, axial stiffening tubes and a wrapper plate overall. The feet of the 25-cycle frame form an integral part of the structure as shown in Fig. 3, while the 50-cycle frame, shown in Fig. 4, has no feet but is circular with two tracks machined on the outside for the supporting rollers of the cradle.

The segmental coreplates, of low loss iron, are carried on dovetail bars accurately located around the inner periphery of the frame ribs. Fig. 5 shows the stator of the 25-cycle machine during core building. The coreplates are clamped between a circular endplate integral with the frame at one end, and a ring of massive cast steel segmental endplates at the other. These can be seen in Fig. 3 which shows the 25-cycle stator just before winding commenced. The coreplates are divided axially into packets by ventilating ducts through which the cooling air passes to the frame which forms a duct leading the air to the exit at the bottom.

The stator windings are of the two-layer diamond or basket type and are of especial interest, as the winding for the 50-cycle machine had to be designed for a normal operating voltage of 22 kV, and therefore to withstand a test voltage of 45 kV. For simplicity the same thickness of insulation, clearances, etc., were also used for the winding of the 25-cycle machine although the normal operating voltage in this case is only 20 kV.

The maximum voltage for which it is practicable to design a basket type winding is probably 22 kV to 23 kV. Not only is a considerable thickness of insulation required for such voltages, but also large clearances and creep distances both between coils of different phase and between all coils and earth, thus making the design of the winding overhang a difficult problem. The coils, each turn of which consists of a number of copper laminations suitably transposed to reduce circulating current losses to a minimum, were accordingly designed so that in the overhang there is a wider gap between adjacent coils of different phase than between those of the same phase. The necessary phase to phase clearance was thereby obtained without unduly extending the axial length of the overhang.

The insulation on the straight portion is of the ' sandwich ' type, which, while it is hot-pressed to form a solid wall of high mica content free from internal voids, also possesses that slight degree of flexibility which is essential for long coils such as these. On the overhang, more flexible insulation with an asphaltum bond is used, and the coils are rigidly braced to withstand the distorting forces resulting from short circuits. The coils are securely lashed to support rings of insulating material, these in turn being supported by a number of brackets, also of insulating material, bolted to the endplates of the stator frame. Fig. 6 shows this construction at the connection end of the 25-cycle machine during winding. At the connection end these brackets also serve to carry the circumferential connections between phase groups, as can be seen in Fig. 7 which shows the completed 25-cycle stator.

Six temperature detectors of the copper constantan thermo-couple type are provided in the winding of each machine.

The end windings are protected by cast aluminium endshields, special provision being made on the

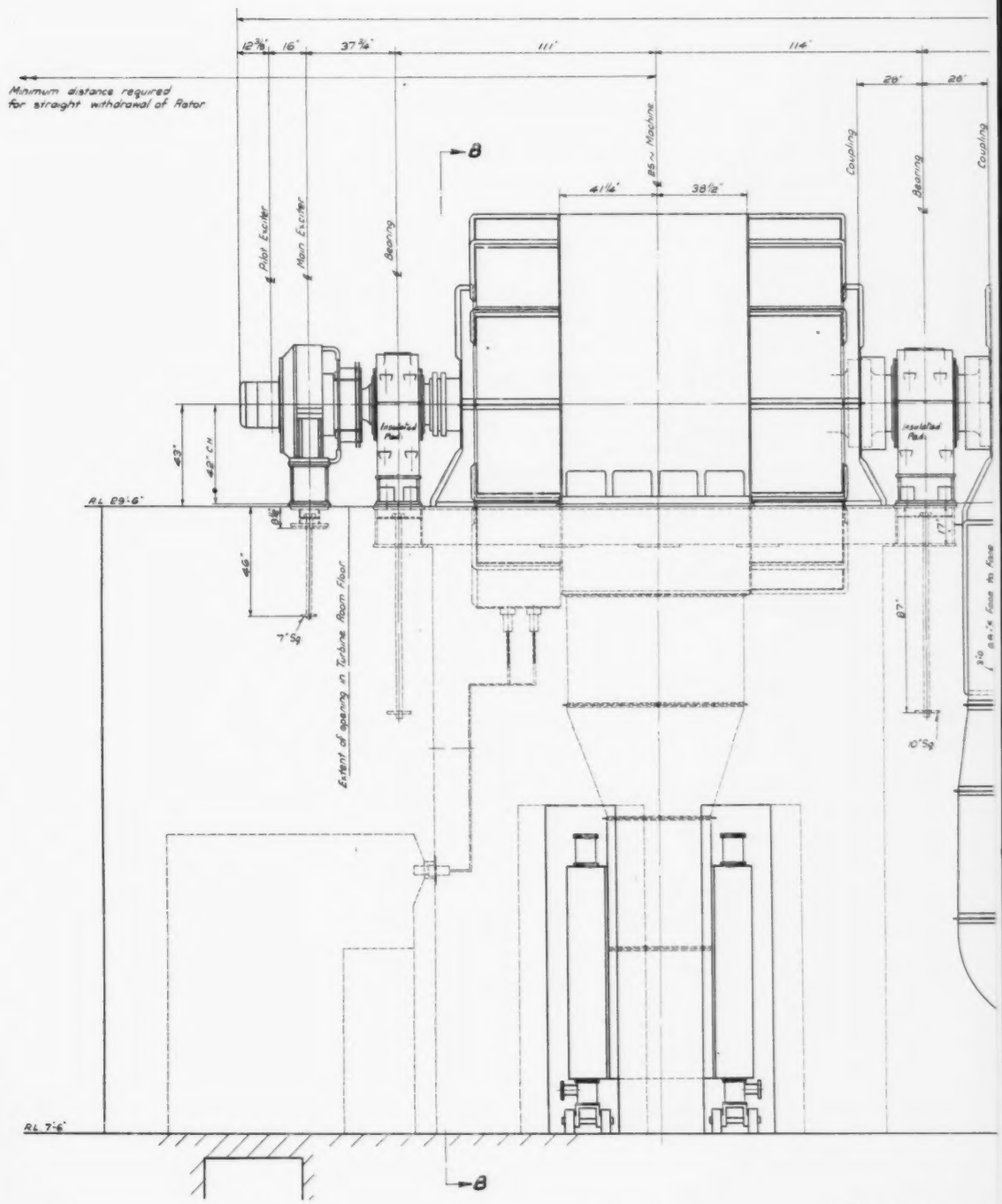
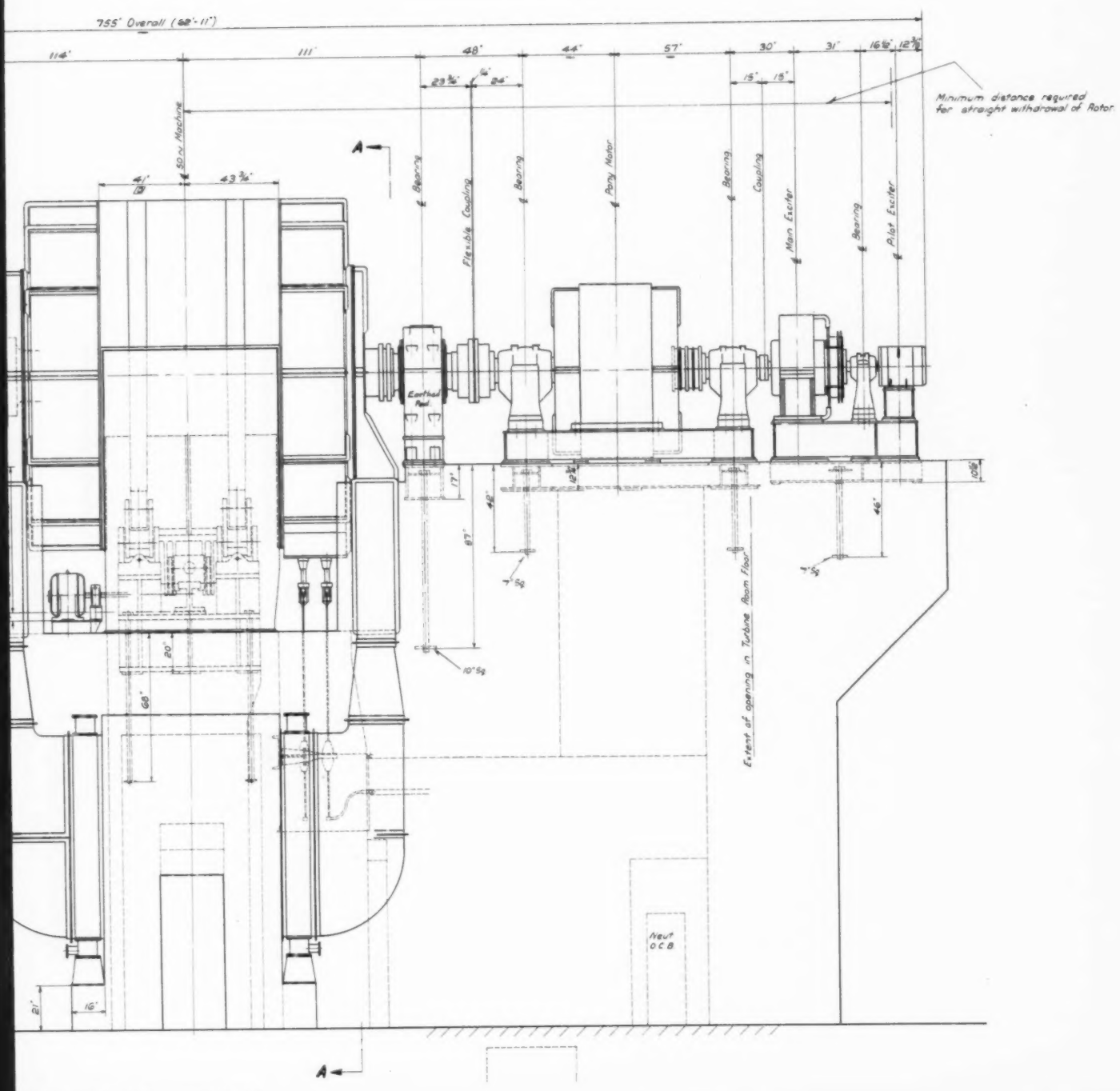
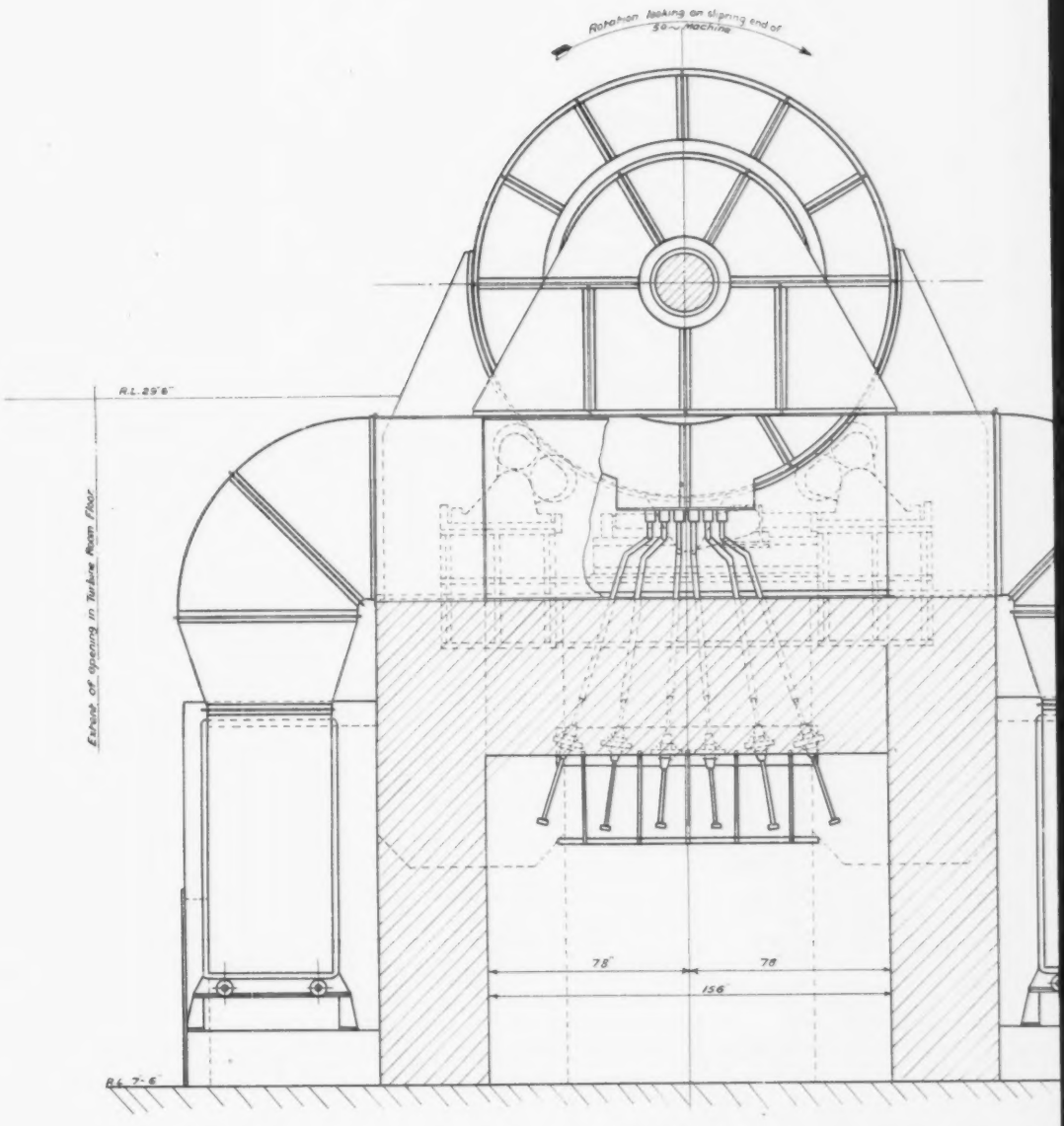


Fig. 1. General

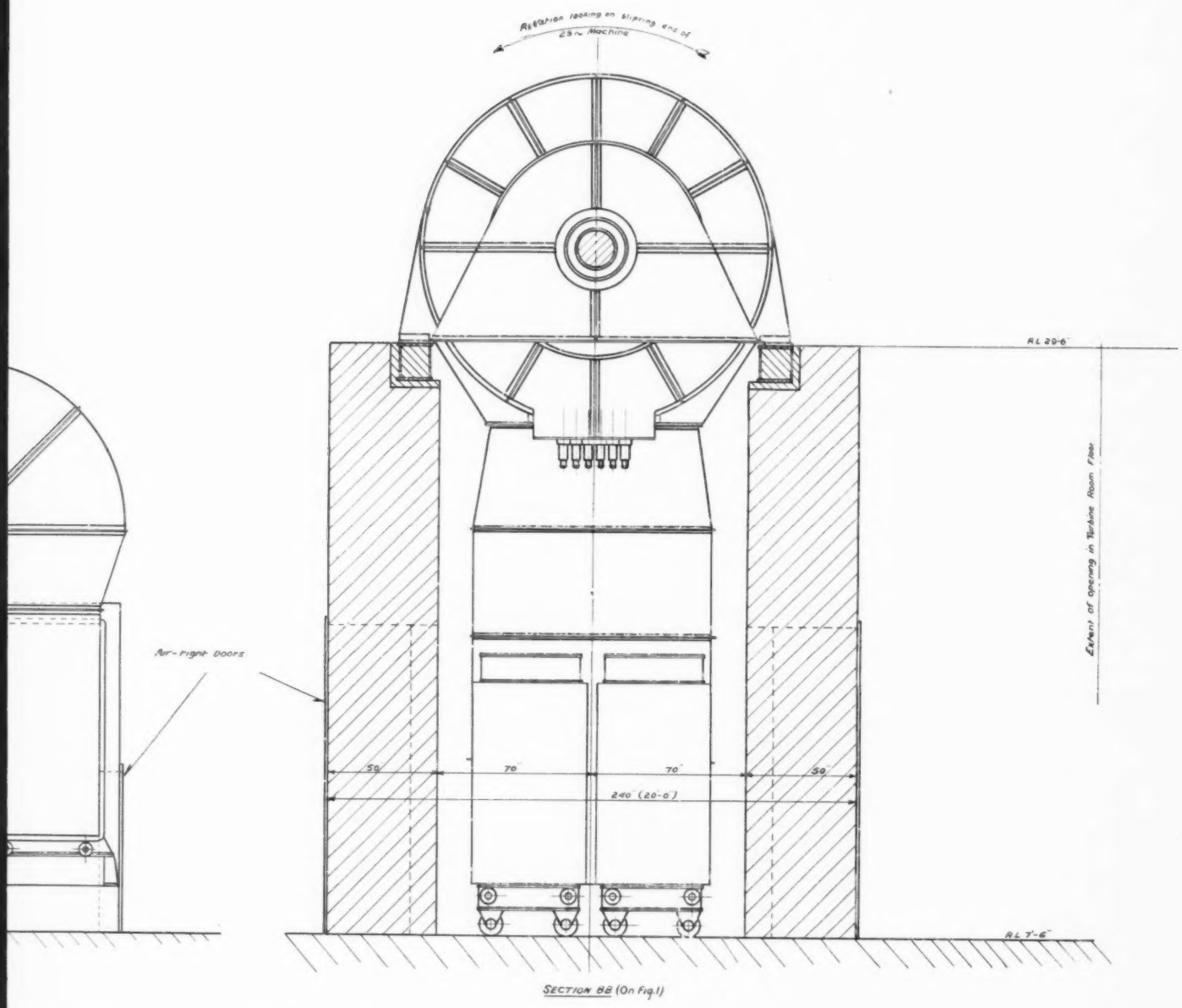


arrangement of the complete set



SECTION AA (On Fig.1)
With part of Trunking
Lockplate omitted to show
terminals

Fig. 2. Trans



erse sections of the 50-cycle and 25-cycle units

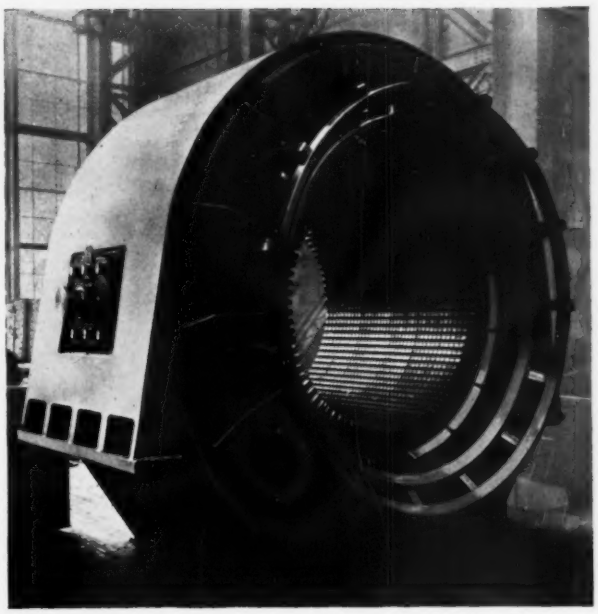


Fig. 3. *The* 25*-cycle stator before winding*

50-cycle machine to ensure that the joints between endshields and fanshields remain air-tight although the former rotate with the frame while the latter are stationary.

In view of the high voltage, the terminals are made of copper rod insulated with condenser type bushings, and are mounted on a terminal plate at the bottom of the outer endshield in each case.

The connection of the terminals of the 25-cycle machine to the busbars is a simple matter, but on the 50-cycle machine the problem is more difficult. The terminals have to swing through 45 mechanical degrees, and the connections between them and the busbars must therefore be flexible while at the same time they must be able to withstand the high line to line voltage over the whole range of travel of the terminals. Cables insulated for 22 kV would have been too rigid, so a linkage system was devised. This consists of six bare copper links, one hinged to each terminal stalk, current being carried across the joint by a pair of short flexible cables. At the lower end these links can slide through condenser type bushings pivoted on gimbals. The motion of the terminals themselves is thus reproduced on a much smaller scale by the bottom ends of the links, so that it is then comparatively easy to connect these ends by flexible leads to the busbars. The links are so designed and the gimbals are so positioned that the clearance between adjacent links is never less than 9 inches at any point in the whole travel. Insulating barriers are fitted between the bottom flexible leads, but the leads are designed so that they will not come into contact with one another even should they be attracted to their extreme positions under the action of short-circuit forces.

Rotors

The rotor body of the 50-cycle machine,

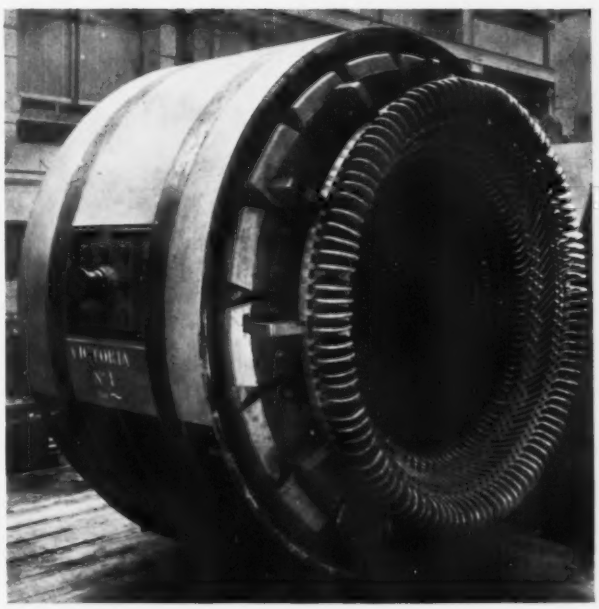


Fig. 4. *The* 50*-cycle stator with winding complete*

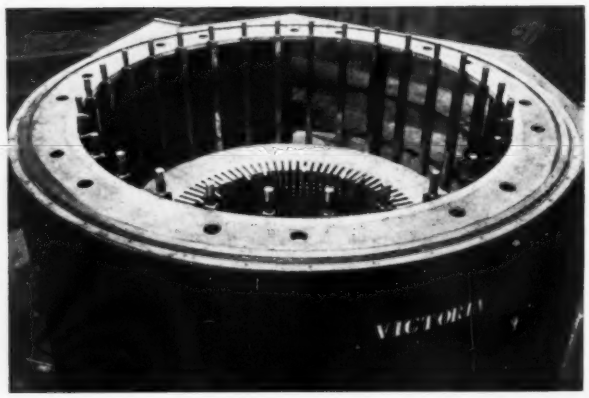


Fig. 5. The 25-cycle stator during core building

Fig. 6. Connection end of 25-cycle stator during winding

shown in Fig. 8, consists of three forged steel slabs shrunk on to the shaft, while the body and shaft of the 25-cycle machine were machined from a single forging which is shown in the lathe in Fig. 9.

The poles, which are built of steel laminations clamped between thick cast steel endplates, are each attached to the rotor body by a pair of T-head projections which engage with similar shaped slots cut in the periphery of the rotor body. Pairs of carefully bedded taper keys lock the poles in position and clamp the field coils between the lips of the pole tips and the rotor body.

Some indication of the enormous centrifugal forces which this attachment must withstand is given by Fig. 10. This shows one of the poles for the 25-cycle machine ; it is about 6 feet long and the span of the pole tip is approximately 3 feet. The pole alone weighs more than 5 tons, and at the overspeed of 900 r.p.m. the centrifugal force acting on the two T-heads due to the pole and field coil is no less than 3,100 tons.

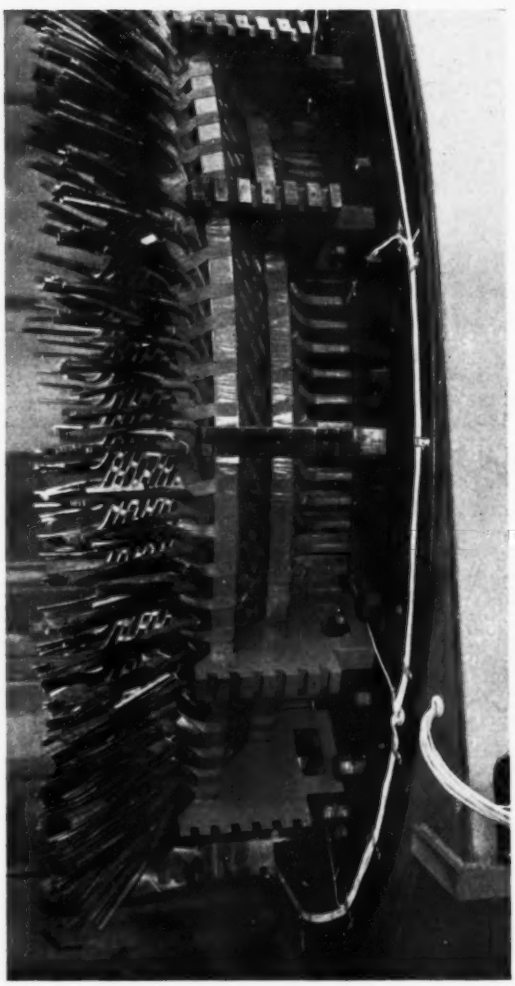
The field coils are of copper strip wound on edge, insulated with asbestos between turns and with mica to earth. To prevent distortion of the copper due to the centrifugal force acting on the turns, three wedge shaped supports are fitted between each pair of poles.

An axial flow type fan is mounted on a separate hub on each side of the rotor body on each machine. Fig. 11 shows the complete rotor for the 25-cycle machine.

As already mentioned, the two shafts are coupled together by a short shaft, the torque being transmitted between the massive couplings by transverse keys.

Bearings and Lubrication System

The three main bearings are of the pivoted pad type. In each the shaft is supported on two whitemetal-lined pads, free to tilt about the axial line pivots on



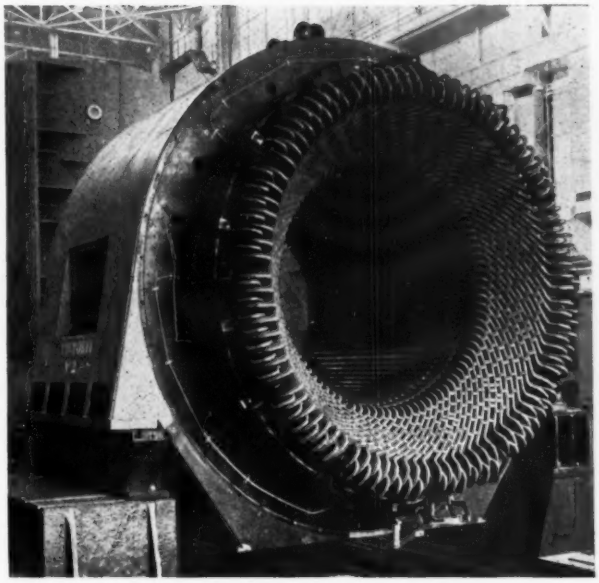


Fig. 7. The 25-cycle stator with winding complete

which they rest, thus permitting the formation of an oil wedge between each pad and the shaft as the latter rotates. The pedestal caps are also lined with whitemetal and are designed to act as reservoirs, normally kept filled with oil, which in an emergency ensure a steady trickle of oil to the pads. The pedestals of the middle and 25-cycle end bearings are insulated from earth to prevent circulation of shaft currents.

The pony motor bearings and the 50-cycle exciter bearing are of the sleeve type with oil rings.

Oil is pumped from a sump tank in the basement via a water-cooled oil cooler to the main and pony motor bearings, whence it drains back to the sump tank from the wells in the pedestals. In addition to the main pump which is driven by an A.C. motor, a standby pump is provided. This is driven by a D.C. motor, connected to the station battery, which is started up automatically should the output from the main pump fall below a predetermined level. Complete failure of oil supply to the bearings is therefore almost impossible.

Flow indicators fitted in the feeds to the bearings are provided with contacts to sound an alarm should the flow to any bearing fall below a predetermined value. Each bearing is also provided with an indicating thermometer which has contacts set to sound an alarm should the temperature of the bearing rise more than a few degrees above its normal operating value.

Ventilation System

25-CYCLE MACHINE

The concrete block which supports the stator forms a closed pit below the machine. At the bottom of this pit are two pairs of water-cooled air coolers on the transverse sides of a sheet steel duct connected to an opening in the bottom of the stator frame. Hot air passing radially outwards along the ventilating ducts in the stator core is collected in the stator frame and led down to this opening and so to the coolers. Passing through the coolers, the air

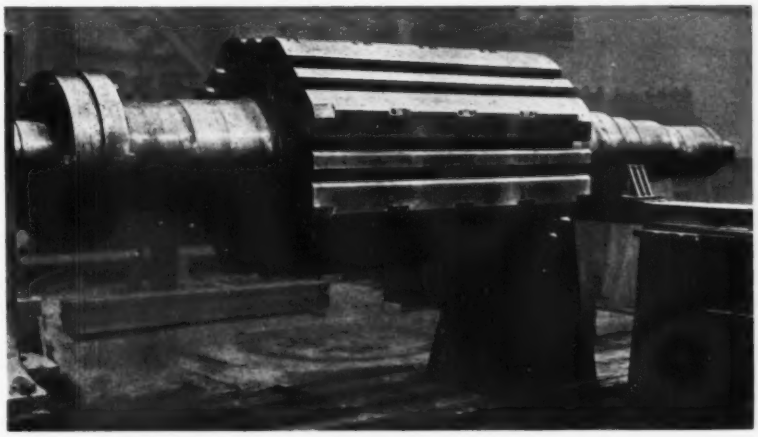


Fig. 8. The 50-cycle rotor hub

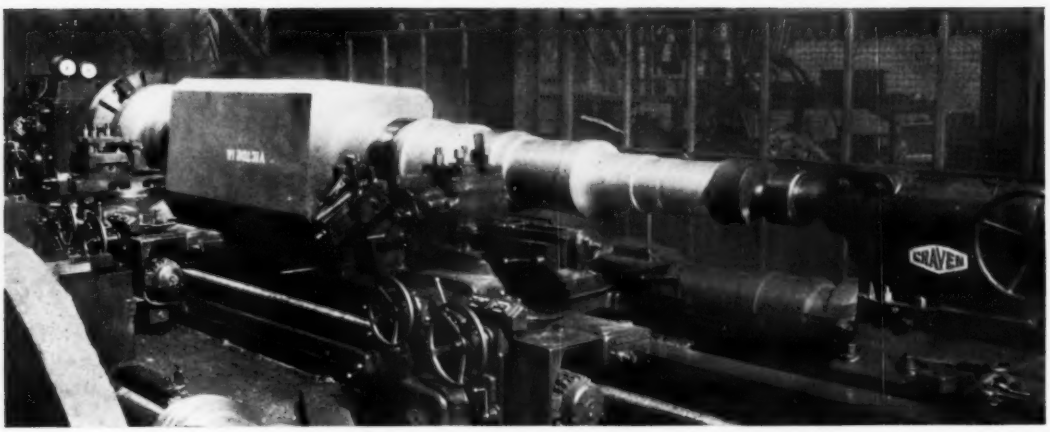


Fig. 9. Initial machining of 25-cycle rotor hub forging

enters the pit, from which the fans draw it back into the machine via two fanshields which connect openings at the top of the pit to the fan inlets of the endshields.

The cooler tubes are made of aluminium brass to resist the corrosive effects of the sea water which is used as the cooling medium, and are wound with a spiral fin to give good heat dissipation. The coolers are mounted on rollers so that when necessary they may be wheeled out of the pit through openings in the axial walls until they are clear of the machine and can be reached by the station crane.

Fig. 10. A 25-cycle pole and keys

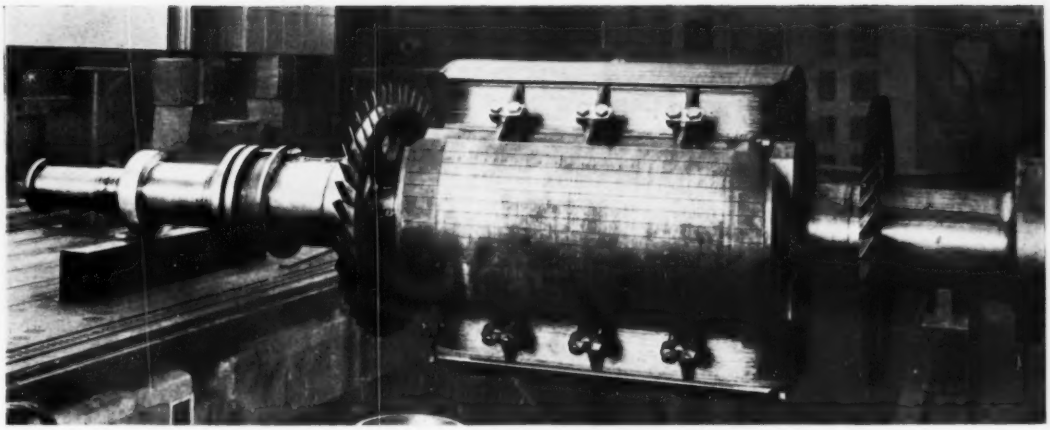


Fig. 11. *Complete rotor for* 25-*cycle machine*

50-CYCLE MACHINE

The ventilation problem was in this case complicated by the fact that the stator must rock through 45 mechanical degrees. Over the whole range of travel of the stator, the opening through which the hot air issues moves within a duct. This embraces the lower half of the stator, a felt seal preventing escape of air at the joints, and is connected to the opening in the top of the concrete block which supports the rocking-gear cradle. The hot air is thus led down to the pit formed by this block, and thence to four coolers mounted on the sides of the chambers projecting from the axial walls of the block. Sheet steel ducts then lead the cooled air to the fanshields which are connected to the rotating endshields by spring-loaded metal to metal joints to prevent escape of air.

The coolers are of similar construction to those of the 25-cycle machine, but are not mounted on rollers as they are already accessible to the crane.

Rocking Gear

Any frequency changer operating on two systems which are linked by other frequency changers must include provision for phase adjustment before synchronising and for control of load sharing after synchronising. Even if there are no other links, such provision is very desirable if both systems have generating plant feeding into them. Thus, in this case, if the frequency changer is taking power from the 50-cycle system, the frequency generated by the 25-cycle machine may be exactly the same as that of the 25-cycle system (if the other frequency changers are operating it must be) but the machine terminal voltage may not be in phase with the system voltage, i.e., the vectors representing these two voltages may be rotating at the same speed but may not be in phase. Before synchronising they must be brought into phase. After synchronising, if the two systems are already linked by other frequency changers, the share of load taken will depend on the phase angle between these two voltage vectors, so that an increase of load must be effected as on any other generator by forcing the 25-cycle rotor forward in the direction of rotation, i.e., advancing the machine voltage vector, and *vice versa* for a decrease of load or reversal of power flow.

As the two vectors may be out of phase by any angle up to 180 electrical degrees before synchronising, it must be possible to rotate the machine voltage vector through any angle up to 180 electrical degrees to bring them into phase. Rotation of the 25-cycle voltage vector through 180 electrical degrees requires a rotor movement of 90 mechanical degrees. Reversal of the 50-cycle machine field current turns the rotor in steps of 45 mechanical degrees, and to set it to any intermediate position it is therefore necessary to make provision for rotating the stator of the 50-cycle machine through 22½ mechanical degrees each side of the mean position, i.e., a total travel of 45 mechanical degrees. Rotation of the stator also permits the

small adjustments of load angle necessary when varying the load on the set.

It has already been mentioned that the need to rock the 50-cycle stator through such a large angle introduced difficulties into the design of the outgoing terminal gear of this machine, and into the design of its ventilating system. As the stator weighs approximately 80 tons, and as the sudden torque which may be exerted on it in the event of a short circuit may be of the order of 1,100 tons-feet, it will be appreciated that the design of the rocking gear itself also presented many problems.

Fig. 12. *Rocking-gear cradle and operating mechanism*

The stator is supported by a massive cradle which rests on the concrete foundation block. The cradle, shown in Fig. 12, consists of a deep 'I' beam spanning the pit in the concrete block transversely, and four pedestals, two at each end, which with the beam form a single fabricated structure of great strength and rigidity. On each pedestal is mounted a housing in which is pivoted a sheave carrying two rollers. The circular stator frame rests on these four pairs of rollers, machined surfaces on the outside of the frame forming tracks on which they run. The frame is located axially and is anchored against the upward force which the short-circuit torque exerts on one side, by claws, fitted to the housings, which engage with projections on the frame. The positions of the housings may be adjusted by jackscrews during erection, but once the stator centre-line has been set to its correct position the housings are locked in position by pairs of taper keys.

The beam supports a slide rail along which a nut is driven by a lead-screw, the latter being driven at approximately 18 r.p.m. through a reduction gear by a 20 h.p. induction motor. The nut is connected by links to a torque bracket attached to the bottom of the stator frame, so that movement of the nut along the lead-screw rotates the stator.

The torque on the stator which would result from a short circuit of the generator could cause a sudden force on the nut of as much as 165 tons. To withstand this force the lead-screw is carried in a pair of spherical roller thrust bearings at the driving end, the bearing housing being mounted on the end of the slide rail. The force is thus transmitted to the cradle. The spherical roller bearing also acts as a journal bearing, and the other end of the screw is carried by a normal roller bearing.

Micro-switches operated by cams on the nut are set to trip the contactor in the feed to the driving motor, and light a warning lamp, when the stator nears the end of its travel. Further protection against over-travel is given by two three-pole limit switches, one at each end, which break the circuit feeding the motor directly if the nut moves a small distance beyond the point at which the micro-switch should have caused it to stop.

Whenever the motor circuit is broken, whether by micro-switch, triple-pole limit switch or by the manual control switch, a solenoid-operated brake is automatically applied to the motor shaft. This brings the nut and stator to rest almost instantaneously, so permitting very fine adjustment of the stator position and preventing damage due to overshoot of the nut at the ends of the travel.

The total nut travel between micro-switches actually permits slightly more than the 45 degrees minimum requirement, and the time for the travel

from one extreme position to the other is almost ten minutes.

The nut and all moving joints are grease lubricated by the Farval centralised system, whereby a pre-set quantity of grease is automatically delivered to each lubrication point by a single manually operated compressor.

Starting and Load Control

The pony motor is a slipring induction motor, wound for 3,300 volts and capable of providing the 9,300 h.p. required at breakaway from rest, although its M.C.R. is only 4,000 h.p. It is connected to the 22 kV busbars via a transformer, the primary of which is in series with the stator winding of the main 50-cycle machine. On closing the main breaker, voltage is applied to the pony motor and speed is gradually increased by the reduction of the loading resistance in its rotor circuit, this being effected automatically. When running at subsynchronous speed, excitation is applied to the main machine field winding and this machine then pulls into step. A breaker short-circuiting the transformer primary is then closed, and the starting cycle is complete. This sequence of operations can be effected automatically or, alternatively, step by step under manual control.

If the two systems are already connected by one or more other frequency changers, the frequency of the 25-cycle machine will automatically be exactly the same as that of the 25-cycle system. If there are no other frequency changers in operation, the frequencies of one or both systems must be adjusted until the 25-cycle machine and system frequencies are exactly the same. Excitation is then applied to the 25-cycle field winding, and the 50-cycle stator rocked—the field being reversed as well if necessary —until the 25-cycle terminal voltage is in phase with the system voltage. With the excitation adjusted to equalise these voltages the 25-cycle breaker may then be closed.

If power is already being transferred between the two systems by other frequency changers, then by further rocking of the 50-cycle stator the set may be made to transmit any required share of the total power being transferred, the power transferred by the other frequency changers automatically falling by a corresponding amount. The share of subsequent changes in the total power transferred may be controlled in the same manner.

Tests

The set was fully tested in the factory before despatch. The tests carried out on each of the main machines included determination of losses, heat run, instantaneous short-circuit for determination of transient and sub-transient reactances, determination of negative and zero sequence reactances, high pressure and overspeed. A full set of running tests was also carried out on the exciters and on the pony motor. All results were extremely satisfactory. The frontispiece shows the set erected in the factory during these tests.

Conclusion

All the many problems involved in the design and manufacture of this unusual set were successfully overcome, and the results of the very thorough range of factory tests prove that the finished machines fully justify all expectations and guarantees.

Present-day Applications of Fibrous Glass Insulation

By E. FARMER, B.Sc. (Eng.), A.M.I.E.E., and J. WAINWRIGHT, A.M.I.E.E., Grad. I. Mech. E., Assoc. A.I.E.E., A.P.I., Insulation Engineering Department.

As it is some years since an article devoted entirely to the subject of fibrous glass insulation appeared in this Journal[1], a review of the present position is considered timely.

Although the early optimism that this new insulation would revolutionise insulation techniques has not been borne out, it is an undoubted fact that glass insulating materials have become an almost indispensable help to the electrical insulation engineer.

In the fourteen or fifteen years since fibrous glass became available to the electrical industry there have been no outstandingly new developments, but as the supply position improved and as experience was gained with this material its use has been extended to many new applications.

This article discusses the reasons for the position which glass now occupies in the electrical insulation field, and describes the forms in which the materials are available and the ways in which they are used in the construction of electrical apparatus. Some notes are also given on the basic manufacturing techniques by which the glass materials are produced.

The Present Position

The fact that fibrous glass is entirely a synthetic material does not enable it to be so formulated and contrived that it possesses no disadvantages and therefore represents the perfect insulating material. This seems to apply to most synthetic materials in which although specific properties of the older natural materials have been improved other properties are decidely inferior. It is for this reason that frequent warnings are given on the correct choice of synthetic materials[2].

The position occupied by fibrous glass can best be assessed by considering the reasons which have made it an almost indispensable material for electrical insulation.

The classification of electrical insulating materials on the basis of operating temperatures is the most useful starting point. Until a few years ago there was fairly universal agreement in the specifications of various countries[3] that insulating materials could be divided into four groups on the basis of maximum operating temperatures. These groups were referred to as Classes O, A, B and C. Of the four, only A and B are of practical importance. Basically, insulating materials are subdivided into those of organic and those of inorganic origin. For instance, Class A materials are organic in origin (*i.e.* containing elements such as carbon, hydrogen, oxygen, nitrogen, sulphur, phosphorus, etc.) and Class B materials are inorganic in origin although the cements and bonds used in their manufacture come from organic sources. A few years ago, with the commercial development in the United States of America of semi-organic cements and bonds, particularly the silicone materials[4], a new insulation class was added to the range. This Class H comprises Class B materials with semi-organic cements replacing the organic types. More recently other subdivisions (Classes D, E and F) have been suggested but these have no particular bearing on the present discussion and will not be considered here.

Materials suitable for the three important Classes A, B and H together with the generally accepted maximum operating temperatures for these classes are summarised in Table 1[5].

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1 *C. D. Jamieson. Woven-glass insulation for electrical windings. E.E. Journal* (Nov. 1940) *Vol. X No. 2, p. 61.*

2 *V. E. Yarsley. The limitations of plastics. Trans. Plast. Inst. Vol. 19 No. 35, p. 20.*

3 *For example, British Standard 225 and A.I.E.E. Standard No. 1.*

4 *See Trans. A.I.E.E.* (1945) *Vol. 64, p. 90 et seq.*

5 *A.I.E.E. Standard No. 1.*

TABLE I

Class	Suitable Basic Materials	Cements, Varnishes and Bonds	Maximum operating Temperatures, °C
A	Organic materials: paper, silk, cotton, wood	Organic ..	105
B	Inorganic materials: mica, asbestos, glass	Organic ..	130
H	Inorganic materials: mica, asbestos, glass	Semi-organic (at present silicone) ..	180

Although the bonds for Class B insulation are merely quoted in the above table as 'organic', the number of different varnishes covered by this description is considerable. Space here does not permit the discussion of varnishes for electrical equipment, but although there are many suitable bonds it is not always easy to fit a particular material into existing shop techniques. In general, straight phenolic or oil-modified phenolic varnishes are the most popular bonds and impregnants for glass insulation when used in the present-day Class B range.

For the successful insulation of almost any piece of electrical equipment, material in textile form is a practical necessity, and in Table I asbestos and glass are the only two inorganic materials available in this form. Thus for the insulation of most equipments for the Class B or H temperature ranges the choice generally falls on one of these materials. It is not the purpose of this article to conclude that either material is superior, but to show that each has its own particular sphere wherein it excels. Much thinner fabrics and tapes can be obtained in glass than in asbestos, and the electrical and mechanical properties of glass are in general superior, but asbestos has a far higher resistance to mechanical abrasion and is more compatible with the majority of the impregnating resins used in the production of laminated materials.

It should be noted here that although the present classification of materials is on the arbitrary organic or inorganic basis, it is probable that materials will soon be classified on the basis of their ability to withstand certain operating conditions. When this occurs it is possible that several of the newer synthetic fibres, notably polyethylene terephthalate[6] [7] ('Terylene') and the polyamides[7] (the nylons), although organic will be 'upgraded' into higher temperature classes. There will then be more than one alternative material available in fibre form and, as the newer materials must be superior in some respects, the use of fibrous glass may decrease.

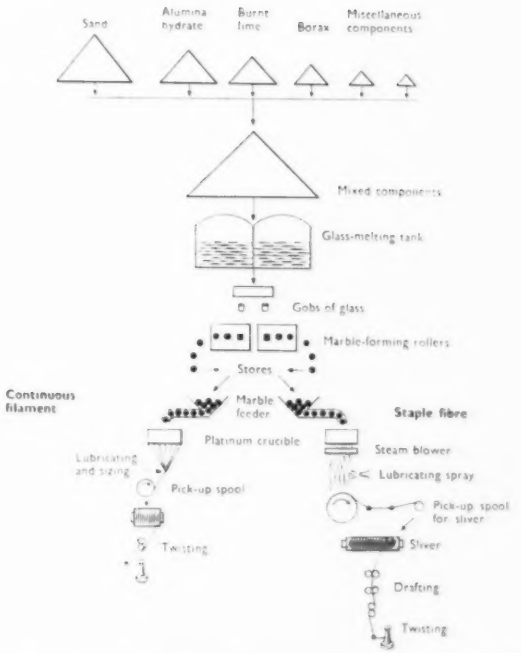


Fig. 1.—Diagrammatic representation of manufacturing process for glass fibres

(By courtesy of Fibreglass Ltd.)

Manufacture of Glass Fibres

Almost all the glass used for electrical purposes is produced in the form of fibres, and is therefore of the type most suitable for fibre-forming. The main constituents are silicon, alumina hydrate, burnt lime and borax, with certain additions to lower the melting temperature, to reduce the tendency to crystallize, and to increase the resistance to weather[8].

6 *Wilson Reddish. Dielectric properties of polyethylene terephthalate. Trans. Faraday Soc.* (1950) *Vol.* 46, *p.* 1010.

7 *C. G. Garton. The properties of insulating materials used in instruments. Proc. I.E.E.* (1951) *Vol.* 98 *Part II, p.* 728.

8 *A. M. Robertson. Fibrous glass electrical insulation. Trans. Inst. Marine Eng.* (1943) *Vol.* 55 *Part* 5.

Fig. 2.—End windings of turbo-alternator, showing coils protected with glass tape and tied with glass cord

This last requirement is due to the enormous increase (more than two thousand times) in the ratio of surface area to weight of the fibre glass over that of glass in more usual forms. It has been found that resistance to weather is a function of the alkali content of the glass. The alkaline oxides of sodium and potassium leach out to the surface of the fibrous glass under humid conditions, producing ionisable salts which in turn attack the glass and eventually destroy the fibre. Only substantially alkali-free glass should therefore be used for glass fibres for electrical purposes[9].

In the manufacturing process, shown diagrammatically in Fig. 1, the raw materials are melted together and formed into marbles approximately $\frac{3}{4}$ in. diameter which are fed into crucibles having either 102 or 204 drawing nozzles in the base. The crucibles are heated electrically and the molten glass emerging from the nozzles is drawn out in one of two ways, depending on whether continuous or staple filament is required.

In the case of the continuous fibre, the filaments are picked away from the nozzles by hand, gathered together on a V-shaped pad, provided with lubrication and binding in the form of a special textile size, passed downwards to a high-speed drawing spindle, and wound up at a speed of over a mile a minute.

Staple yarn, a discontinuous type, is produced by a similar process but the fibre is attenuated by a blast of either steam or air. The fibres fall on to a revolving drum in a broad fine veil which is gathered in sliver form. This is subsequently twisted into yarn which is coarser in appearance than the continuous filament yarn.

Normal textile procedure is used for subsequent operations on both types of fibre.

Properties of Fibrous Glass

From the electrical insulation aspect the most important property of fibrous glass (accepting its dielectric properties) is ability to withstand high temperatures. Its softening temperature is over 800°C which is far above the normal operating temperatures of electrical equipment, although the material is devitrified at 350°C and it is generally found that the abrasion resistance is seriously reduced after heating to temperatures above 250°C. Generally, it is safe to use glass tapes up to 250°C but only in special applications should it be used at higher temperatures[10].

Glass fibre cloth is not in itself an insulator but merely a spacer, *i.e.* its own electrical strength is

9 *Fibreglass Ltd.* (*Publication*) *Fibreglass for better insulation.*

10 *H. Duflos and P. Mathivet. Isolants modernes et les possibilités du verre tissé. Revue Generale d'Electricité* (1952) *Vol.* 61 *No.* 1, *pp.* 20-26.

approximately only equivalent to that of the same thickness of air : in order to make it into an insulator it is necessary to replace the air in the material with varnish. In varnish-impregnated glass cloths and tapes it is the varnish which limits the temperature at which the material may be used, whereas with varnish-impregnated cloths made from cotton, silk or rayon, the cloth is the limiting factor (see Table I). Whilst asbestos cloth will withstand high temperatures, it suffers from the disadvantage of low tensile strength which seriously limits its applications.

Fibrous glass has also the following desirable features :—

(*a*) Low moisture absorption, which is considerably lower than in asbestos, cotton, rayon, etc.

(*b*) Chemical stability.

(*c*) Resistance to attack by most corrosive vapours, which makes it very suitable for use on equipment in steel mills, chemical factories and similar situations.

(*d*) It is resistant to fungus, termites, etc., which makes it very useful for equipment which is to be used in the tropics.

(*e*) The low dielectric loss angle makes it useful for high-frequency applications.

(*f*) The high tensile strength of the glass fibres permits the use of thin cloths and tapes, and the material has therefore a good space factor.

(*g*) The thermal conductivity of the fibres is so high that even the woven fabrics have a comparatively high value of this property.

(*h*) Glass cloth is resistant to fire, which makes it an admirable outer protective covering.

Fig. 4.—*Weaving glass tape*
(*By courtesy of Fibreglass Ltd.*)

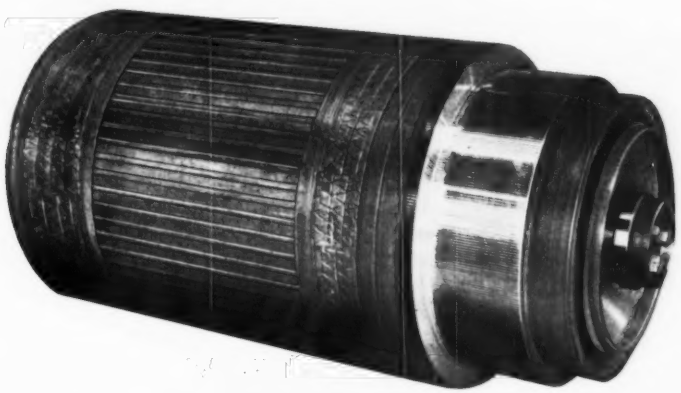


Fig. 3. *Armature of traction motor in which fibrous glass insulation is used*

Fibre glass has one serious disadvantage in its inability to withstand abrasion, which makes it necessary to use considerable care in applying glass insulation and in handling glass-insulated conductors. It is perhaps to this aspect that most thought must be given before glass insulation can be used in a new application.

Although the low moisture absorption is essentially a good feature, it makes the material more difficult to impregnate with varnish than organic materials,

as the glass fibres themselves are non-absorbent. Even so, it is possible to produce a satisfactory varnished glass cloth because the varnish is keyed between the fibres of the yarn.

The Uses of Glass Fibres

Basically, fibrous glass is available as a yarn which may be woven into cloth, tapes, or sleeving. It may also be twisted into cords, or applied as a lapping or a braid to wires and bars.

As a cloth it is normally woven from continuous filament and is available in thicknesses from 2 mils upwards. It is almost invariably used in combination with other materials, mainly as a backing for mica splittings or as a carrier for various varnishes and materials such as silicone rubber[11].

When the glass cloth is used as a carrier for varnish, it is usually cut into tapes which may be either straight cut or bias cut. The former are preferred because of the tendency of bias-cut tapes to 'neck' when pulled, with a consequent reduction in electric strength due to the varnish film fracturing.

To apply mica to conductors it is necessary to use a backing material which must essentially be thin as it is only a means to an end. In designing machines, engineers demand insulation having maximum electric strength with minimum radial wall thickness; customers, through British Standards, demand a high percentage of non-combustible material in the insulation; production engineers demand that the mica tape or sheet should be strong, to avoid unnecessary wastage due to the material breaking during application. Glass cloth fulfils these demands better than any other material yet tried, although it costs a little more than such materials as silk and rayon.

The thinnest asbestos cloth available is approximately 10 mils thick so that, with the design requirements already mentioned, asbestos cannot be used in place of glass for mica backing or as a varnish carrier.

A recent development is the manufacture of a paper made entirely from glass fibres[12]. This material has so far been used only for experimental capacitors but it may prove to be suitable for other purposes.

An interesting combination of asbestos and glass has recently been introduced using glass cloth and asbestos paper, both of varying thicknesses, in arrangements such as glass-asbestos-glass and asbestos-glass-asbestos. The layers are impregnated with a flexible varnish and combine the high tensile strength of the glass cloth with the superior abrasion resistance and electric strength of the varnish-treated asbestos paper. The asbestos also acts as a cushion for the glass, so that the combination has a reasonable compressive strength and is not so liable to damage by localised pressures.

Glass tape is often used as a protective outer covering for insulation because it does not deteriorate with age at the normal working temperatures of machines (Figs. 2 and 3). When it is used for this purpose the tape is always woven as a tape (Fig. 4) and not cut from cloth, as the latter material frays at the edge and tears much more readily. The woven tape is bought in the untreated form but is impregnated with varnish before it is used in order to make it easier to handle and to improve its already low moisture absorption.

The tape can also be used in certain low-voltage machines as inter-turn and eddy-current insulation, but care must be exercised in choosing the machines on which it is used because of its susceptibility to damage in application. Here again the use of a suitable varnish can effect considerable improvement in the abrasion resistance of the glass.

Glass thread is often applied directly to the copper conductor for inter-turn and eddy-current insulation, either as a lapping or as a braiding.

In the first method the thread is wound round the conductor unidirectionally, each turn touching its neighbour, thus giving complete coverage (Fig. 5). Usually the copper is double-lapped and sometimes treble-lapped, according to the requirements of the application. The glass is coated with a varnish to improve the resistance to abrasion and to prevent any movement of the glass lapping. A typical use for wire insulated with glass applied in the form of lapping is in the winding of control coils for 'English Electric' magnetic slip couplings. These coils must be exceptionally strong and this require-

11 *J. R. Read and J. J. Tyner. A new resilient Class H material for the insulation of traction motor field coils. Trans. A.I.E.E.* (1950) *Vol.* 69 *pp.* 1158-1161.

12 *T. D. Gallinan, R. T. Lucas and R. C. Bowers. The electrical properties of glass fibre paper. Report of Naval Research Laboratory (Washington D.C.) May* 1951, *pp.* 5-18.

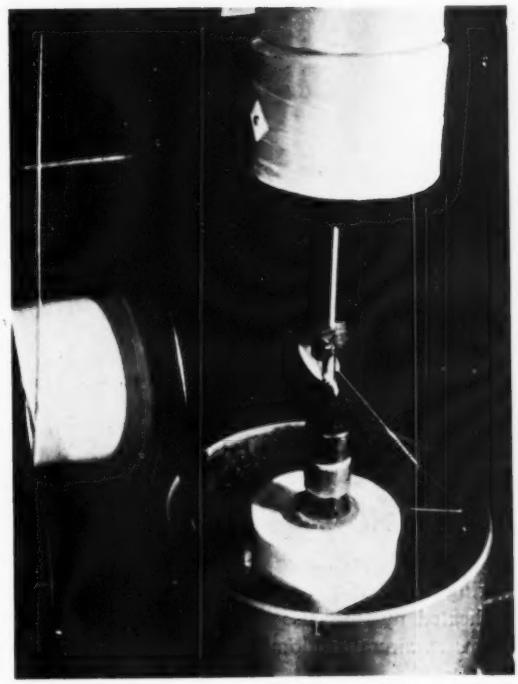


Fig. 5.—Lapping a copper conductor with glass fibre
(By courtesy of British Insulated Callenders Cables Ltd.)

ment is met by bonding the individual turns with an oil-modified phenolic varnish compatible with that used during manufacture of the wire. Suitable impregnation and baking processes produce coils which are completely self-supporting and remarkably rigid. Other applications of glass thread lapping are to coils for mush-wound stators, field coils both stationary and rotating, solenoid coils and transformer coils[13].

In the second method of applying the glass to the conductors, as a braiding, a number of threads are wound-on in each direction by a machine which works on the principle of the village maypole dance (Fig. 6). The thread is varnished after application, partly for the reasons applicable to the lapped covering and partly to fill the voids between the threads, as the covering in this case is much more open than in the lapped covering. The degree of covering naturally depends on the number of threads used and the angle of lay of the threads. Braiding is occasionally applied over lapped glass on stranded conductors to produce flexible leads, but a more extensive use for braiding is in the insulation of rectangular conductors. Lapped and braided conductors can be used in the construction of stator coils for large machines, and a very solid construction can be obtained by bonding in the same way as for the magnetic coupling coils previously mentioned.

Braiding is also available woven in tubular form for application to conductors in short lengths, and it is occasionally used as a tying cord, especially if it is desirable that the cord should be flat as used to secure insulation, for example, at the edges of band insulation or on commutator vee-rings.

Glass is available in various diameters in the form of tying cords which can be used for such purposes as banding the end-windings of large alternators[14], as in Fig. 2. In this application it has two main advantages: firstly, increased mechanical strength to withstand short-circuit forces and, secondly, freedom from the ageing under operating conditions which with organic materials may cause considerable reduction in strength.

The high tensile strength of the fibres also makes it very desirable to use glass cloth as a base for laminates, provided that a good bond can be made to the glass. Unfortunately, the textile size used in producing the cloth acts as a barrier between the resin and the glass, making it impossible to obtain a good bond. With certain varnishes it may even inhibit the polymerisation of the resin, so that it is essential that the size should be removed. The glass may be cleaned by caramelisation, by heat cleaning or by chemical cleaning[9]. In the caramelisation process the cloth is exposed to a temperature of 350°C at which temperature oils and volatiles are driven off and starches and other solids are partly burnt, leaving the cloth a golden brown with the size content reduced from 2 to 0.5 per cent. For heat cleaning the cloth is heated to 500°C when it becomes almost pure white and the size content is reduced to approximately 0.2 per cent. Detergents are also used for washing the cloth and there are numerous special treatments designed to strengthen the glass-to-resin bond. In general, heat cleaning

13 *Melvin L. Manning. The application of Class H insulation to transformers. Trans. A.I.E.E.* (1951) *Vol.* 70 *Pt.* 2, *pp.* 1427-1434.

14 *P. Meinhardt. Install glass ties on stator windings. Elec. World Vol.* 123 *p.* 107.

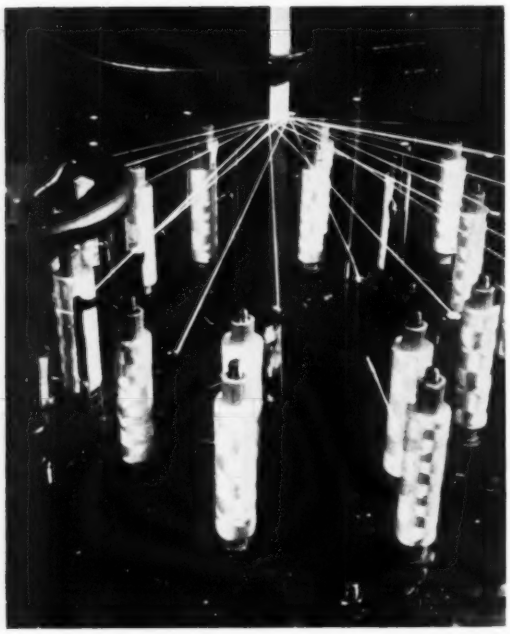


Fig. 6.—Braiding a flat copper strip conductor with glass fibre
(By courtesy of British Insulated Callenders Cables Ltd.)

produces laminates with superior electrical properties, and caramelisation and washing give better mechanical properties.

There are two main ways in which glass laminated materials are made.

The longest-established method is that in which glass cloth, after cleaning by one of the means already mentioned, is impregnated with a suitable resin. The treated material is then cut into sheets and sufficient plies placed together and cured under heat and high pressures to produce boards. The bonds were originally of the phenolic types but silicone resins are now used so as to utilise the higher temperature resistance of the glass[13], and melamine formaldehyde resins mainly on account of their improved resistance to electrical 'tracking'. By selecting the correct treatment for the glass fabric, the correct bond and the correct laminating technique, it is possible to produce boards with the desired electrical, mechanical or thermal characteristics.

The second method of producing a laminated material has been developed during about the past ten years and is generally referred to as low-pressure laminating[15]. It depends for its success on the availability of a class of resins which polymerise without the evolution of water or other volatile substances[16]. It is the evolution of such volatile substances which necessitates the use of fairly high mechanical pressures in the production of conventional laminates, *e.g.* those with phenolic bonds. The newer resins polymerise without producing volatile substances and so, in conjunction with glass fabrics, can produce laminated materials with very low moulding pressures. This makes it possible to mould very complicated shapes without having to make expensive moulding tools. These techniques have not yet been used for heavy electrical engineering applications, but their potentialities are indicated by their use in the production of such items as aircraft radomes, hulls of boats, and car bodies.

Conclusions

Since glass in fibre form became available to the electrical industry its use has expanded fairly rapidly but, with improvements in other materials and the possibility of upgrading new organic materials with respect to temperature, this expansion may be at a slower rate in the future.

The whole range of glass-fibre materials has given excellent results in service, provided suitable applications have been selected and the materials suitably treated. In this respect, the selection of impregnating varnishes is paramount.

Acknowledgement

The authors are grateful to Fibreglass Limited, for providing data and illustrations for this article.

15 *A. Burness. The art of low pressure laminating. Trans. Plast. Inst. Vol.* 18 *No.* 32, *p.* 31.

16 *B. Parkyn. Unsaturated polyester resins. Trans. Plast. Inst. Vol.* 20 *No.* 41, *p.* 36.

Cofrentes Hydro-Electric Development

By H. L. BAZALGETTE, A.C.G.I., M.I.E.E., A.M.Inst.C.E.

ON 26th MAY, 1952, Cofrentes power station was inaugurated by General Franco, Head of the Spanish State, in the presence of several thousands of people. The General started one of the 56,000 h.p. turbines (Fig. 1) and in his speech he referred to the efforts being made by his Government to recover from the ravages of the civil war and to become economically self-sufficient. The Cofrentes development can be regarded as one of the first fruits of those efforts.

At the close of the last European war the Spanish Government took energetic steps to increase their hydro-electric power resources and, after exhaustive surveys, La Sociedad Anonima Hidro-Electrica Espanola placed a series of orders with the English Electric Export and Trading Company for plant and equipment for the extension of the existing Madrid-Millares system.

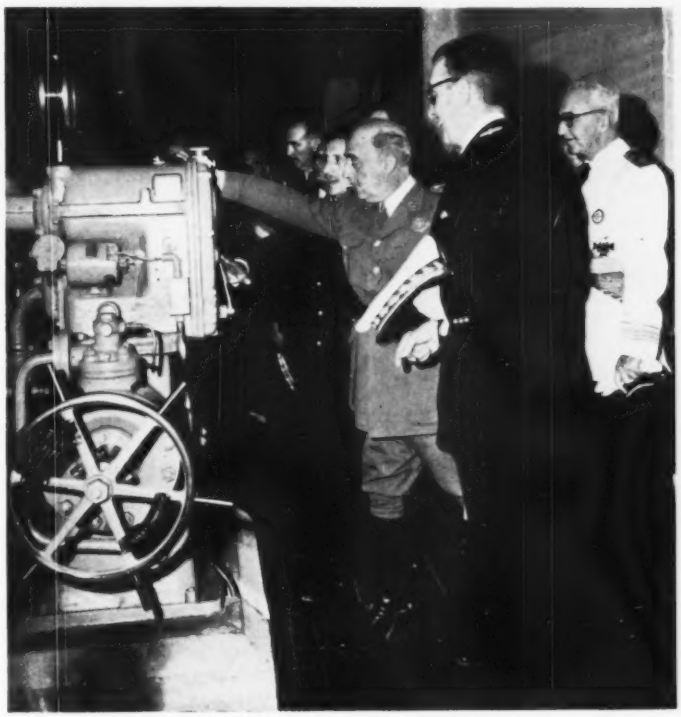


Fig. 1. General Franco starting one of the 56,000 h.p. water turbines in Cofrentes power station

The first and most important contract, awarded in March, 1947, was for the complete equipment of Cofrentes power station which is located at the conflux of the Jucar and Cabriel rivers about 50 miles from the Mediterranean Port of Valencia and some 170 miles from Madrid. The order included three 56,000 h.p. vertical reaction water turbines, 136 metres net head, driving 46,000 kVA alternators at 300 r.p.m., main and auxiliary transformers, auxiliary impulse turbine and alternator, 150 kV outdoor switching station, control and auxiliary switchgear, and power cables. The contract also included the complete pipelines, the power station crane and various other auxiliary equipment, and was therefore of the comprehensive character which the 'English Electric' organisation is so well fitted to execute.

Cofrentes power station forms part of an extensive system, the hydraulic layout of which is shown in Fig. 2, and the principal data for each of the power stations included therein are given in the following table.

Station.	Turbine altitude, metres above sea.	Gross head, metres.	No. of sets.	Output in kVA Per set.	Output in kVA Station.
Villora	672	112/114	2	17,500	49,500
			1	2,500	
			2	6,000	
Alarcon	757	56/22	1	13,000	20,300
			1	7,300	
El Picazo	697.8	51.5	2	10,000	20,000
Tranco del Lobo	475	12	2	1,600	3,200
Cofrentes	322	136	3	46,000	138,000
Cortes	234	78	2	18,750	37,500
Millares	83.5	141	4	25,000	100,000
				Total	368,500

The Madrid-Millares 150 kV system, of which Cofrentes power station now forms part, is shown in Fig. 3, and the main electrical connections at Cofrentes are shown in more detail in Fig. 4. Alarcon reservoir on the Jucar river is designed for inter-annual regulation and will have a capacity of 700 million cubic metres of water in the first stage of development and 1,100 million cubic metres in the final stage. The water is intended for irrigation in the low-lying land behind Valencia after passing through the power stations shown in Fig. 2. Consequently Cofrentes and the other power stations will work at maximum intensity in the summer, a very valuable feature in Spain where the summers are long and dry.

The storage reservoir for Cofrentes power

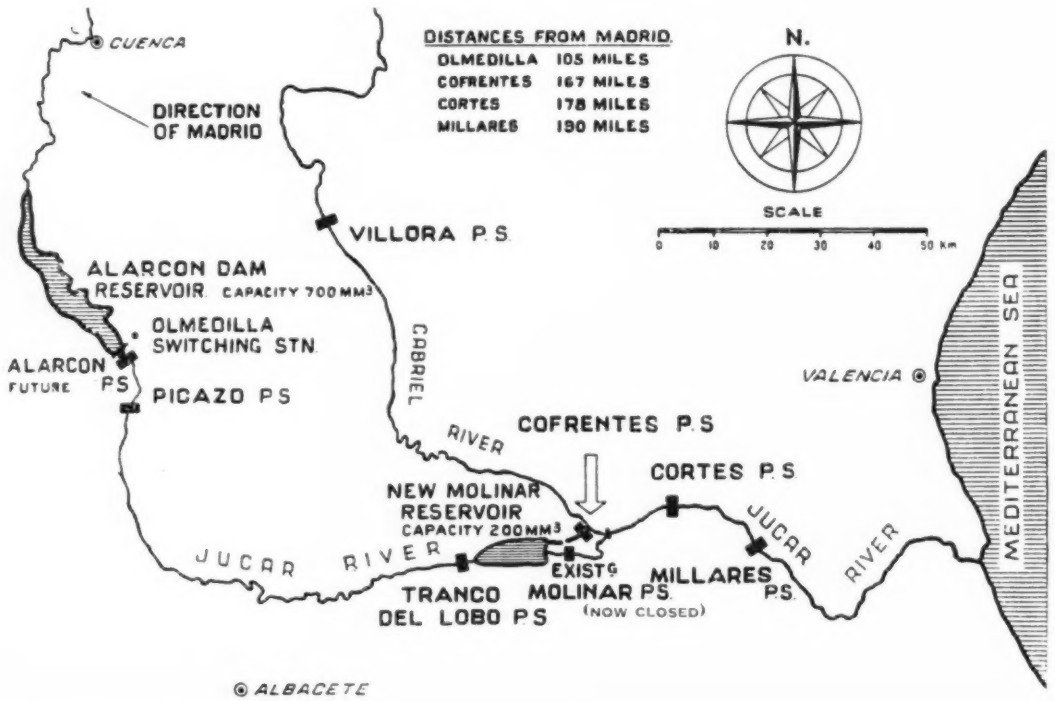


Fig. 2. Hydraulic layout of the system in which the Cofrentes development is included

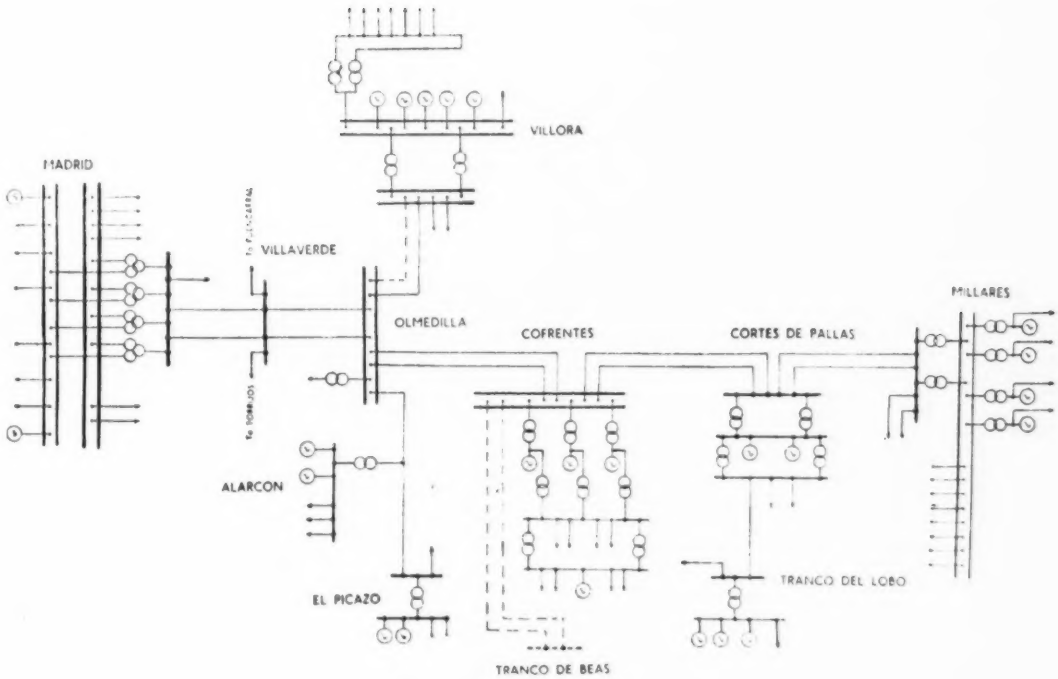


Fig. 3. The Madrid-Millares 150 kV system

station itself is at Molinar, where a new dam has been built and the water is led by a tunnel through the mountains for 14 kilometres to a headpond (Fig. 5) from which it falls through the pipelines to the power station (Fig. 6) and is ultimately discharged into the Cabriel river.

An unusual feature is that now the Cofrentes station is in service, Molinar power station is deprived of water and is shut down. The latter station went into service in 1910 and was the first power station to be operated by Hidro-Electrica Espanola. The feeder from Molinar is at 70 kV which was at that time the highest transmission voltage in Europe.

The turbines, generators and switchgear for El Picazo power station are being supplied by The English Electric Company, and the station is arranged for remote control from Olmedilla switching station, the equipment for which has also been supplied by this Company.

Pipelines

As already mentioned, the order included the three pipelines connecting the forebay with the turbines, and these were sub-contracted to the South Durham Steel and Iron Company Ltd., of Stockton-on-Tees. Each pipeline consists of about 450 metres of steel piping having an inside diameter tapering from 3 metres in the top section to 2.8 metres in the bottom section and with thicknesses varying from 13 mm. at the top to 26 mm. at the bottom.

The pipes were manufactured from pairs of plates with the two longitudinal seams electrically butt welded. All plates have a tensile strength of 26/30 tons per square inch, a minimum yield stress of 30,000 pounds per square inch and an elongation of not less than 25% on a length of 8 inches. The straight pipes were made in 3-metre lengths and two such lengths were then welded together to form 6-metre lengths for shipment ; three 6-metre long pipes (one 3 metres dia., one

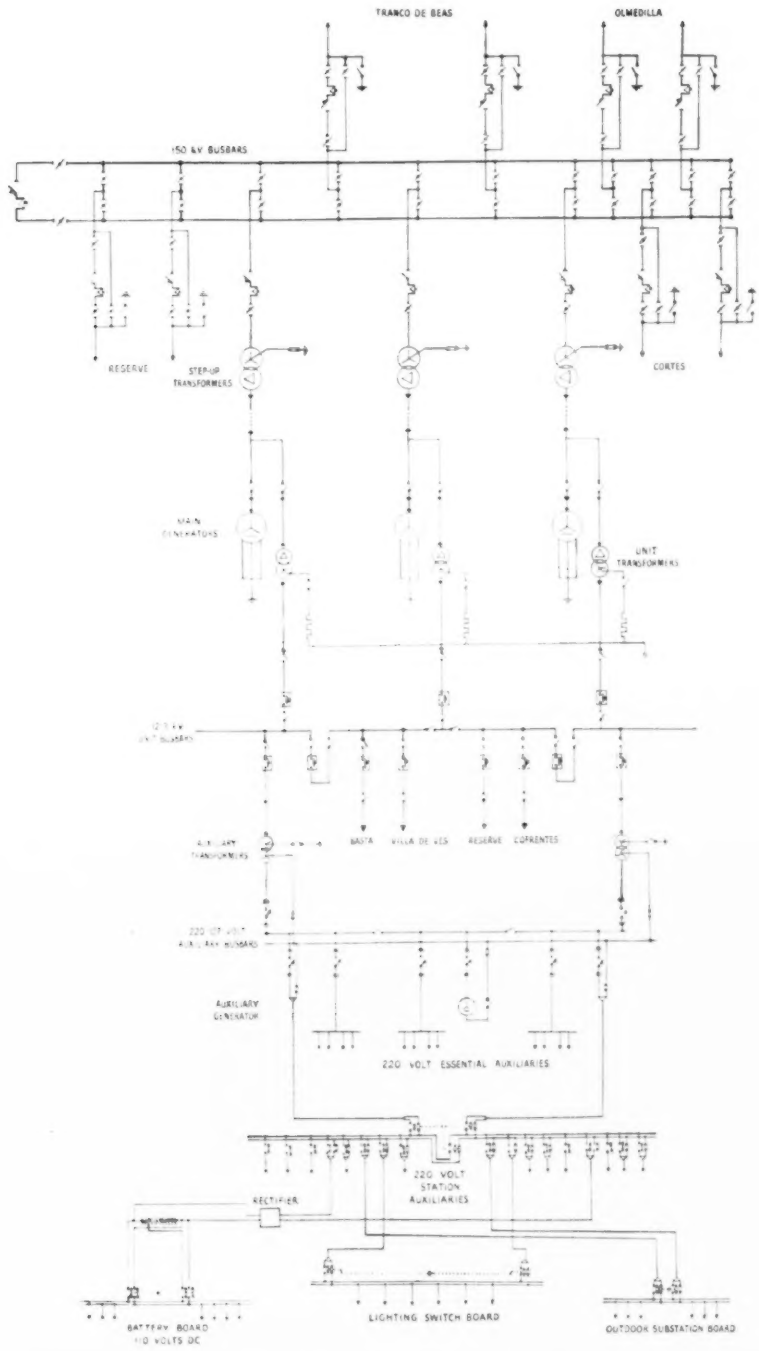


Fig. 4. Main electrical connections at Cofrentes

2.9 metres dia., and one 2.8 metres dia.) were nested together, the maximum weight of one nest being about 25 tons.

The pipes, bends and expansion joints have circumferential strap joints, and the straps were electrically welded to the pipes *in situ*. All joints were assembled in the maker's shops and the pipes were marked to ensure correct reassembly.

The bends are of the 'lobster back' type and the expansion joints of the packed gland slider type fabricated throughout from mild steel. Pipe supports are provided at 9-metre centres throughout the pipeline.

Two of the assembled pipelines are shown in Fig. 7. The third pipeline was not in position when the photograph was taken.

Turbine Room Layout

The arrangement of the turbine room is shown in plan in Fig. 8 and in elevation in Fig. 9. It will be noted that it is of the one-floor type which enables all parts to be within easy reach of the crane, including the main inlet valves.

All the auxiliary equipment such as governor actuators with their servomotors, oil pumping sets and pressure receivers, strainers, and machine instrument panels, are located in the turbine room and disposed conveniently at the foot of the concrete generator pedestals. The generator itself is bolted to soleplates and is carried on a reinforced concrete plinth.

Provision is made for the easy removal of the turbine runner from below by making the upper part of the draught tube removable, leaving an opening which leads to an extension of the valve pit from which the runner can be removed by the crane. The auxiliary unit is placed under the dismantling bay, and adjacent to it is the impulse turbine driven standby governor oil pump.

The station is served by a crane, supplied by

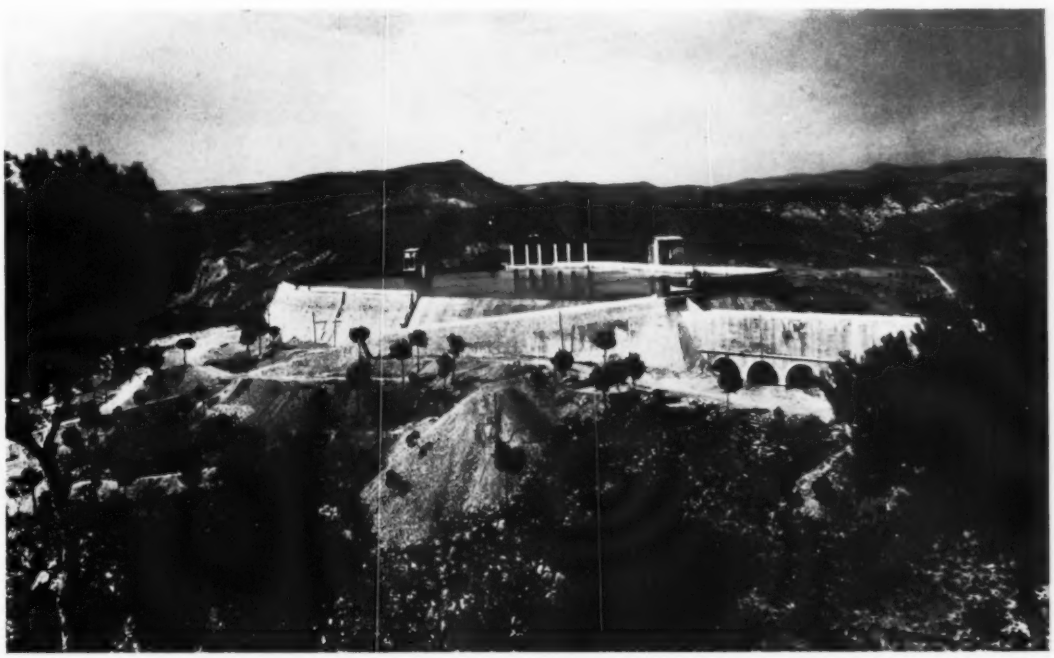


Fig. 5. The headpond, with inlet pressure aqueduct, spillway and lead-off channel

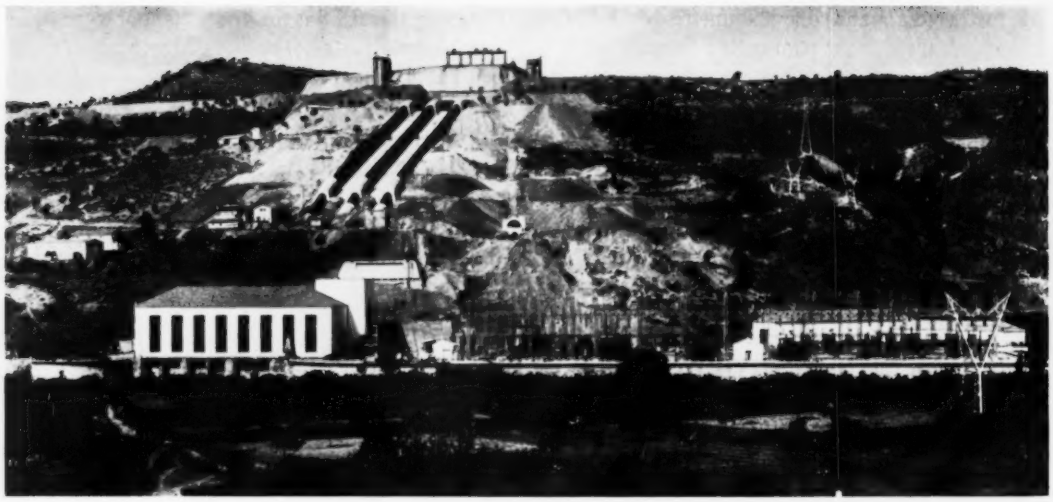


Fig. 6. Cofrentes power station, with pipelines and headpond above and switching station on right

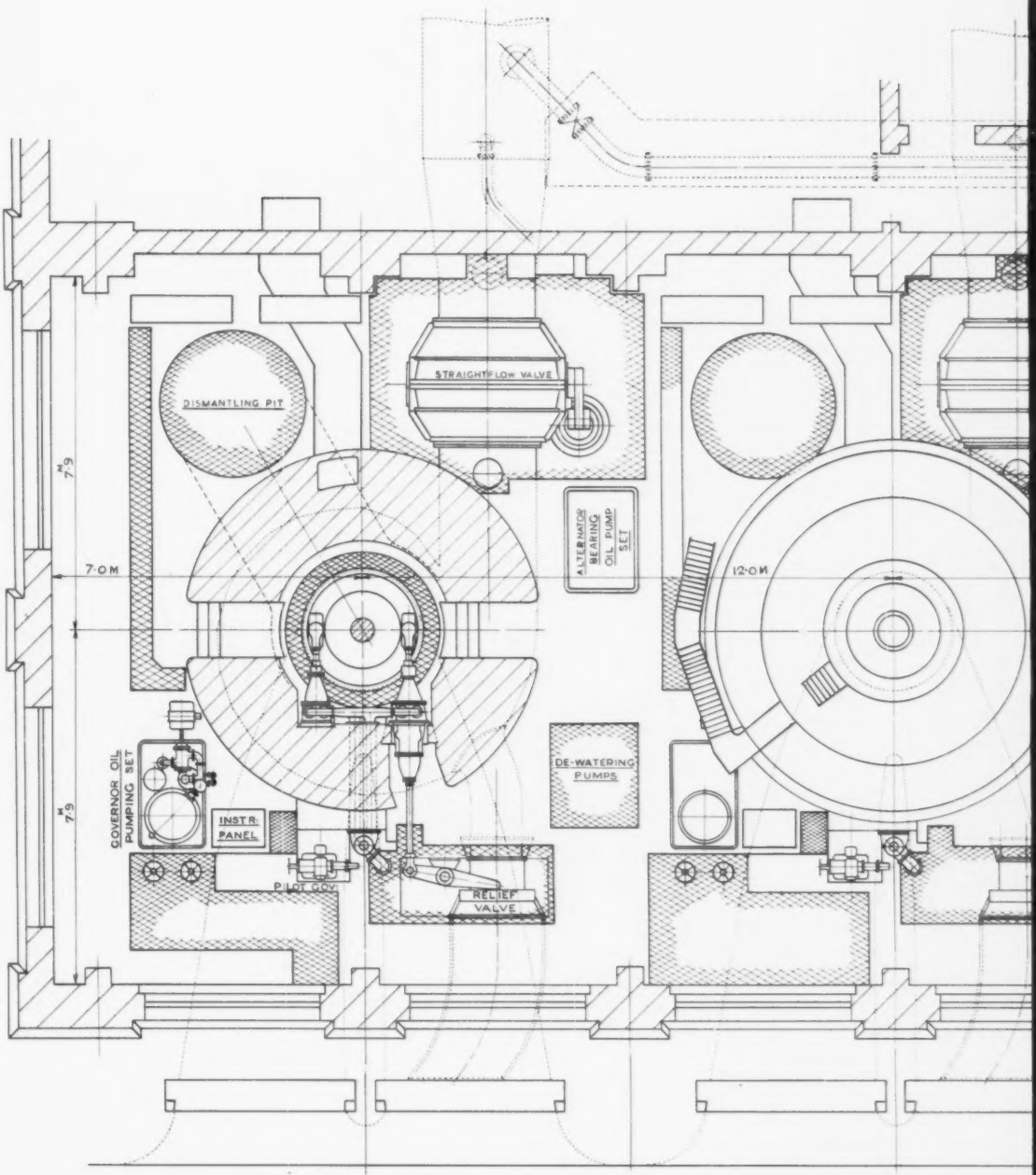
Fig. 7. An early site view showing two of the three pipelines assembled

Sir William Arrol & Company, designed to handle a maximum working load of 175 tons and with an auxiliary hoist of 20 tons. It has the motions of hoisting, travelling and traversing operated by independent electric motors.

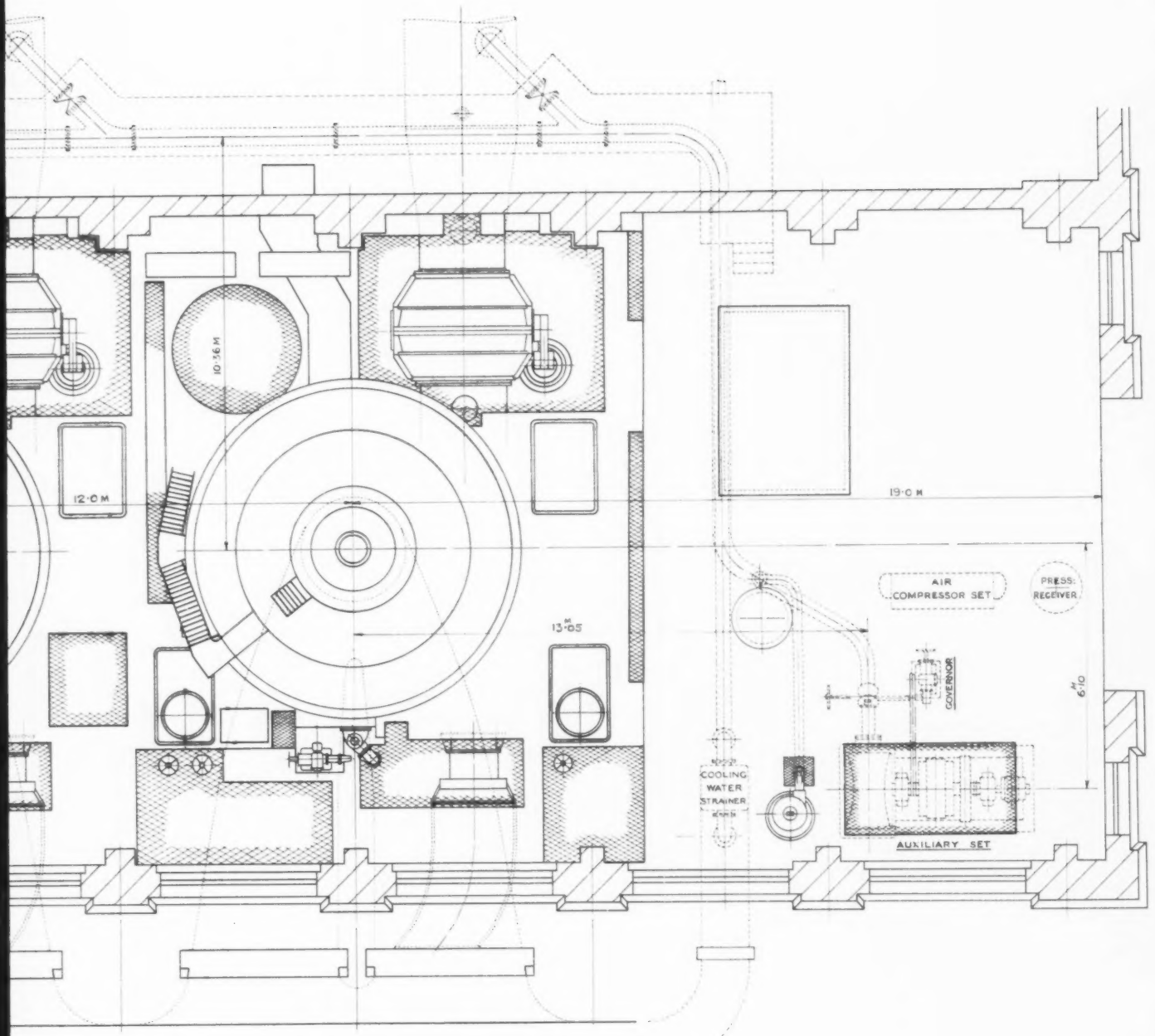
Main Turbines and Valves

The main water turbines are of the vertical shaft reaction type designed to give 56,000 h.p. under a static head of 140 metres and a net head of 136 metres, and to run at 300 r.p.m. A sectional assembly is shown in Fig. 10.

The turbines have spiral casings of 2,140 mm. inlet diameter built up of electrically welded mild steel plates graduated in thickness to suit the load, with butt joints between plate segments. Each casing was welded to the steel speed ring at the works, the whole forming four complete sections joined together by welding at site. The swivel


DISMANTLING PIT
STRAIGHTFLOW VALVE
ALTERNATOR BEARING OIL PUMP SET
7·9M
7·0M
7·9M
12·0M
GOVERNOR OIL PUMPING SET
INSTR: PANEL
PILOT GOV:
RELIEF VALVE
DE-WATERING PUMPS

Fig



. 8. Plan view of turbine room

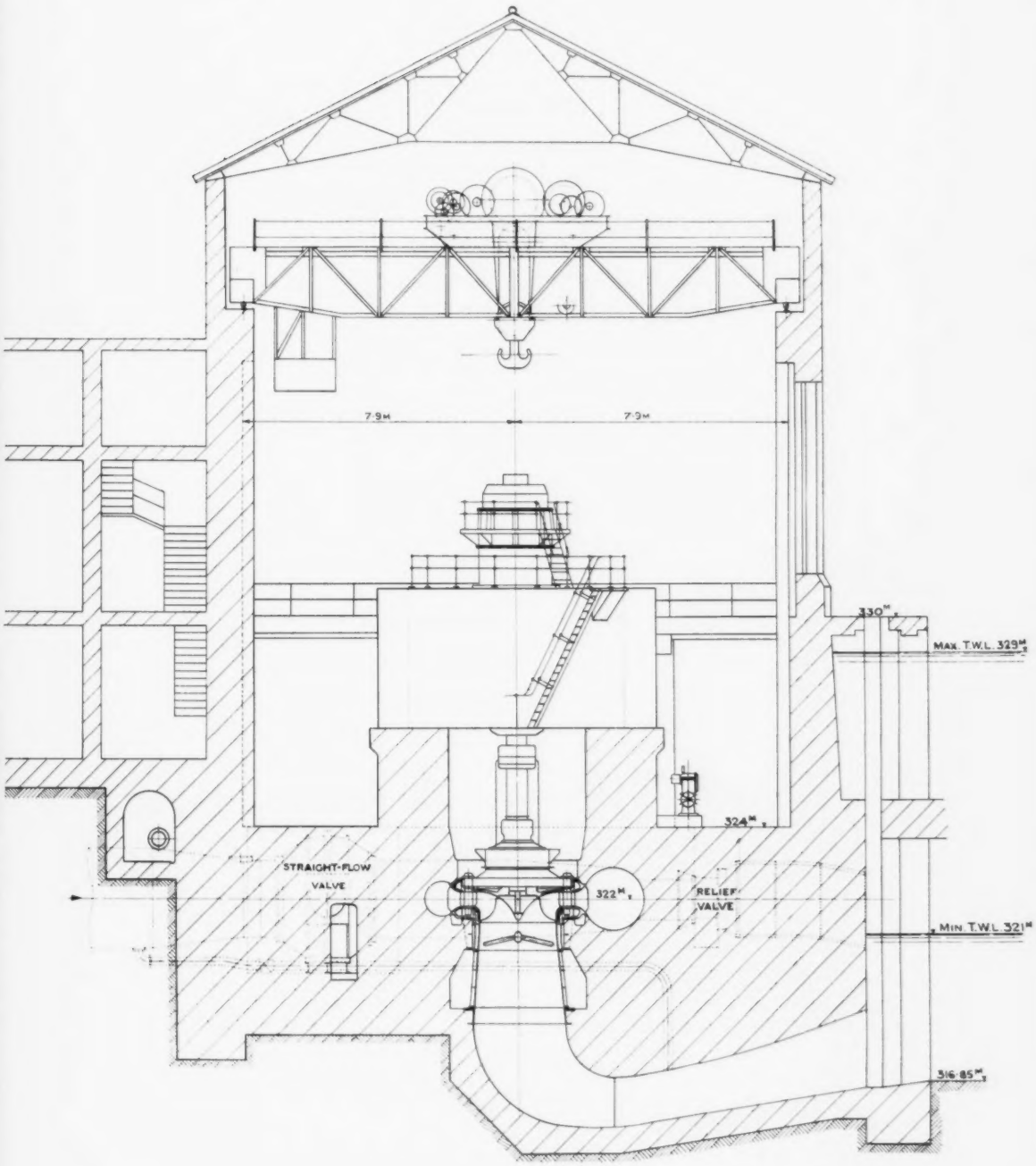


Fig. 9. Sectional elevation of power station

gates are of steel, integral with their trunnions, the vane bodies being made of stainless clad steel.

The runner is made of stainless steel with ground and polished streamlined vanes and steel labyrinth sealing rings. The main cover is of electrically welded steel of box construction provided with a flange for the central bearing section, gunmetal bushed bearings for the swivel gate trunnions and facings for the regulating ring. The latter is of welded steel with gunmetal gliding pads, and is provided with cast iron swivel gate levers and links and two steel rods directly connected to the pistons of the operating servomotors.

The turbine bearing consists of a welded steel housing in halves, bolted and dowelled to the turbine cover, and a cast iron bush in halves lined with anti-friction whitemetal.

The lubricating system for the turbine bearing comprises two pumps, each capable of delivering all the oil required, one gear-driven from the main shaft and the other, used as a standby, driven by an A.C. motor. The standby unit can be brought into service by means of an oil pressure relay, and it is also used to flood the bearings when starting up.

Each turbine is equipped with an automatic oil pressure governing system on the usual ' English Electric ' principle. It includes the governor actuator with servomotor and operating levers, speed adjustment device for synchronizing, a device for shutting down the turbine from the control board, and protective devices for shutting down in the event of governor drive failure or of insufficient governor oil pressure. Each governing equipment also includes an oil pressure receiver and oil pumping set of sufficient capacity to operate any two sets of turbine gate mechanisms by means of interconnected oil pressure systems. Two servomotors are provided for operating the regulating ring of each turbine directly through connecting rods, the oil pressure supply to the servomotors being controlled by a distributing valve.

Each turbine is equipped with a cylindrical balanced relief valve of 1,120 mm. bore, controlled by the movement of the governor servomotor piston. This valve is arranged to give a straight discharge and is mechanically operated by means of oil pressure ; it thus avoids the risk of silting up, attendant on hydraulic operation with water of the nature encountered on this project.

The turbine main valves are of the Company's Straightflow type, 2,130 mm. bore, and, as in the case of the relief valves, they are operated by oil derived from the governor oil pressure system. They are designed to close against maximum flow in emergency. The valve consists of a main body of spherical form made in halves of electrically welded mild steel, and a cylindrical inner body which acts as a prolongation of the pipeline. The valve door is hemispherical and has a solid section which closes the pipe bore, and a pierced section which coincides with a gap in the main body and so continues the smooth pipe bore when the valve is open. The door is operated by means of a powerful servomotor with control gear for hand opening and remote electrical closing. When shut, leakage through the valve is prevented by a rubber seal forced by water pressure in the pipeline against a stainless surface on the door.[1]

This design of valve possesses the great advantage of presenting a straight and smooth pipe bore to the water when open but is always capable of closing safely, and in emergency, because the hemispherical door cuts through the water flow without deflecting it. Water hammer is eliminated by regulating the movement of the operating servomotor by means of a travelling control screw which moves with the valve cylinder, reduces the supply of oil and so progressively diminishes the speed of closing.

Main Generators

The three main generators are each designed to give an output of 40,000 kVA at 0.9 power factor, 13,800 volts, 3-phase, 50 cycles, and run at 300 r.p.m. Each machine is also capable of giving a continuous overload of 15% and is designed to run with safety at the maximum overspeed of the turbine, 543 r.p.m. Each machine has a synchronous condenser capacity, when over excited, of 30,000 kVA at zero power factor and, when under excited, of 28,000 kVA.

The machines are of the vertical shaft two-bracket type, a combined thrust and guide bearing

[1] *The Straightflow valve and its seals were illustrated in the December 1952 issue of this journal, Vol. 12 No. 9, pp. 11 and 12.*

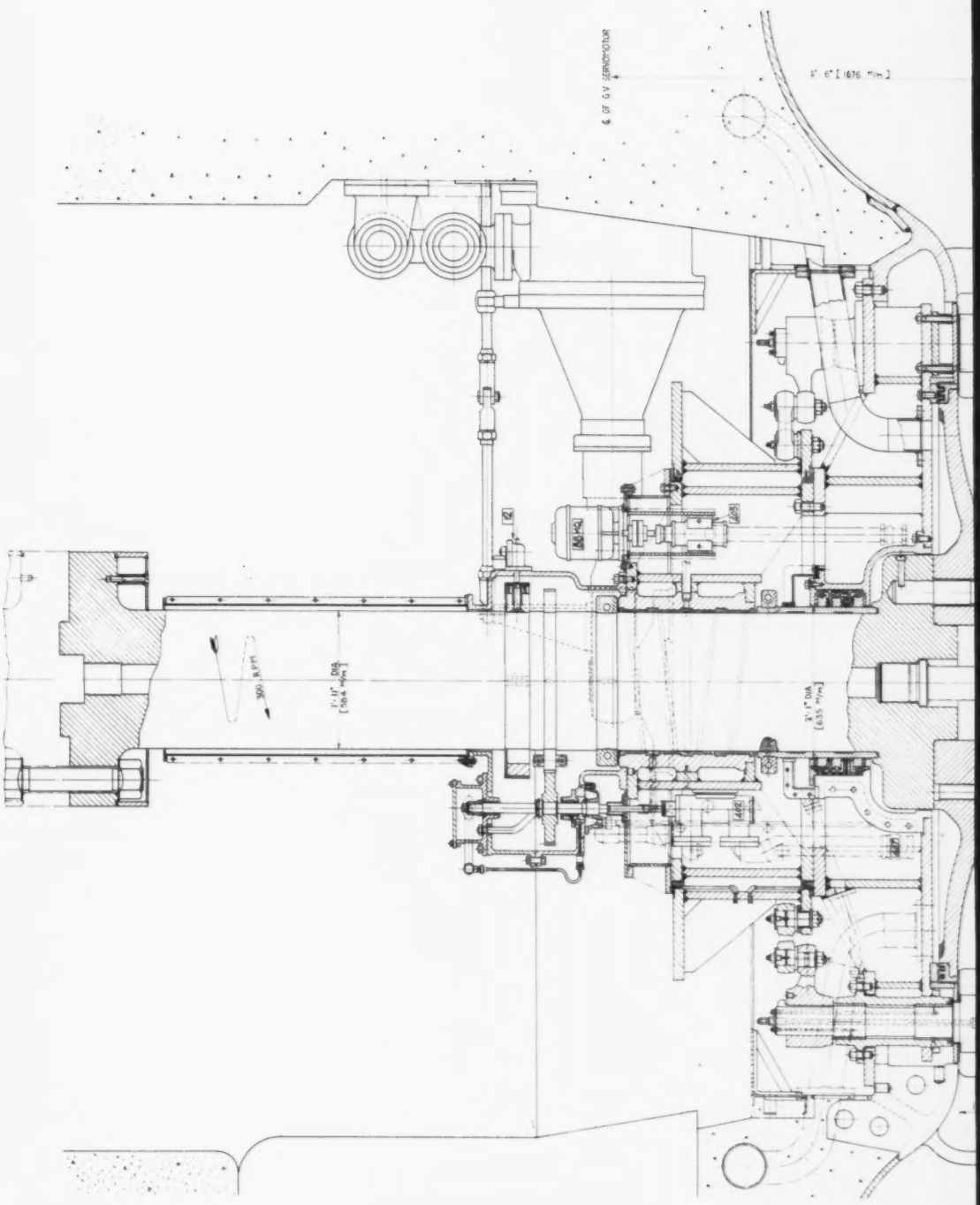
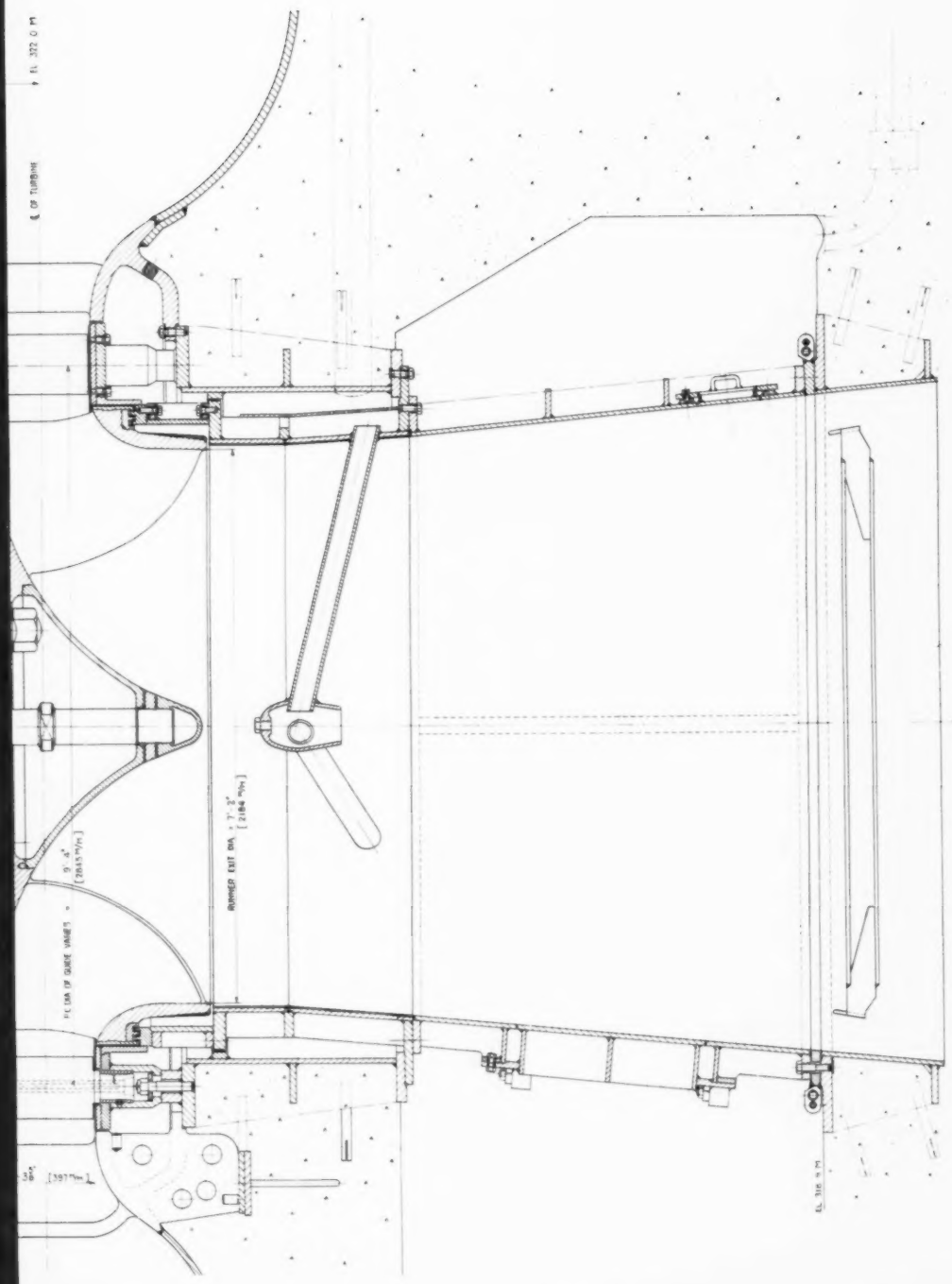


Fig. 10. Sectional assembly o



f 56,000 h.p. turbine

being mounted in the upper bracket above the rotor, and a second guide bearing below the rotor in the lower bracket. The stator frame is built up of steel elements welded together, and to facilitate transport it is divided into two sections bolted together.

The core laminations are stamped out in segments and are built up in short packets of graded length to give equal temperature distribution in the core. The core was pressed at frequent intervals during manufacture and is finally secured against vibration by massive end fingers and is clamped between the frame end-plates. The whole core was tested magnetically before winding.

The stator winding is of the two-layer basket type with conductors built up of laminated copper. The insulation is Class B in accordance with B.S.226. Six temperature detectors are embedded in the winding, and an indicating instrument and alarm for excessive temperature are provided.

The rotor hub is constructed of thick plates shrunk on the shaft, with dovetail slots in the periphery to receive the poles which are made up of sheet steel laminations riveted between end plates. Both pole and end plate are dovetailed and are fitted with taper side-keys into the slots in the rotor rim ; this facilitates removal for repairs. The field coils are formed of copper strip on edge, and to prevent distortion or shrinkage they were pressed while hot during manufacture with a pressure in excess of that exerted on the outer turn at runaway speed.

The whole weight of the revolving parts is carried by a thrust bearing of the pivoted pad type mounted in the upper bracket. The rotating load is transmitted through a thrust bell which is lightly pressed on to the shaft and secured by keys. The thrust bell has a highly polished face and the pads are pivoted to enable them to tilt freely in any direction ; they are also flexibly mounted and independently adjustable to ensure that each carries its due share of the load.[2] The thrust bearing runs in an oil pot which also contains a guide bearing, and the oil is circulated by an A.C. motor driven pump supplemented by a D.C. motor driven pump to act as standby.

The upper bracket is of cast steel and consists of a central hub with six arms, the solid upper face of the hub forming the seating for the thrust bearing. A second guide bearing is mounted in a lower bracket between the rotor hub and the coupling and is included in the same lubricating

[2] *See "Thrust bearings for vertical shaft water turbine driven generators by J. B. Young, E. E. J. March* 1953, *Vol.* 13 *No.* 1 *p.* 13.

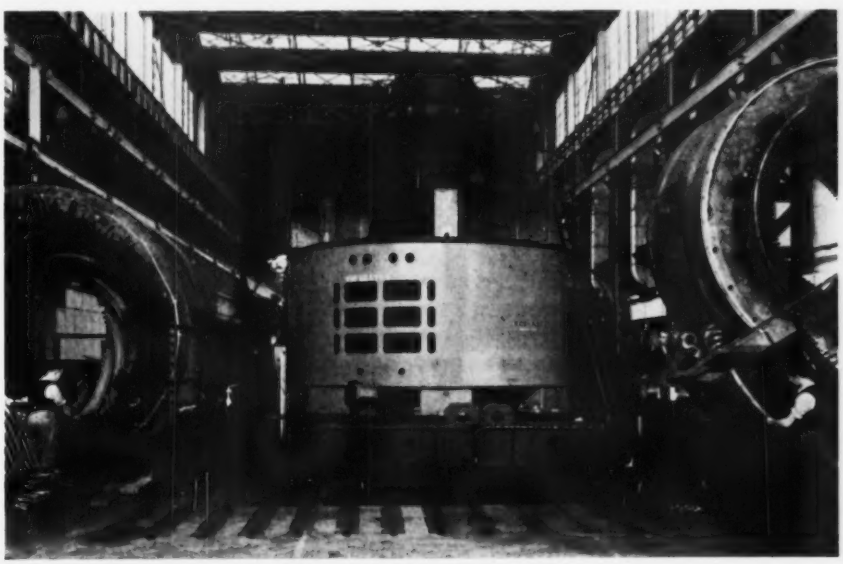


Fig. 11. *One of the main alternators on test at Stafford Works*

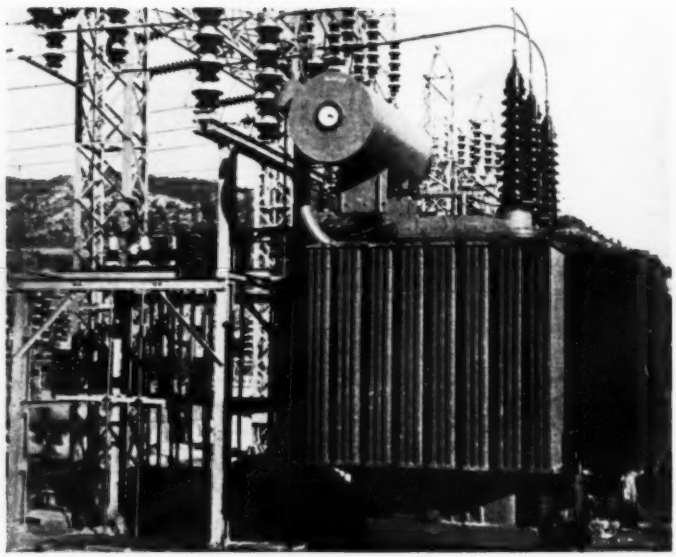


Fig. 12. *One of the main step-up transformers during installation at the switching station*

system as the thrust and upper guide bearings.

Each of the arms of the lower bracket carries a braking and jacking cylinder supplied with compressed air for braking and oil under pressure for jacking. The brake shoes are Ferodo lined and press against a brake track on the underside of the rotor, which can be brought to rest from full speed in a few minutes. The compressed air equipment consists of two A.C. motor driven compressors, and the oil for jacking is supplied from a portable hand operated pump. After jacking, the rotor can be maintained in position by follow-up screws.

The generators have closed-circuit cooling, the air being circulated by fans attached to the rotors and cooled by eight water-cooled air coolers arranged radially outside each stator frame.

The governing of the unit is electrically controlled and for this purpose a governor alternator is mounted on the main shaft directly above the thrust bearing ; this supplies an electric motor which drives the turbine governor actuator pendulum. Main and pilot exciters are included on each unit, and automatic voltage regulator equipment is provided with the switchgear.

One of the main alternators on test at the works is shown in Fig. 11.

Auxiliary Generating Set

To provide a source of supply for the station and unit auxiliaries a separate turbine driven generator is provided. The turbine is of the single jet impulse type with horizontal shaft, and gives 600 h.p. at 500 r.p.m. under a net head of 136 metres. It has an oil pressure governing system of a similar type to those serving the main turbines. The alternator is capable of 500 kVA at 0.9 power factor, 250 volts, 3-phase, 50 cycles. It has two pedestal bearings on a bedplate, and a thrust bearing at the driving end to take the hydraulic thrust of the turbine. A flywheel is provided to ensure good governor regulation. An exciter is coupled direct to the alternator shaft.

Transformers

The three main outdoor step-up transformers are each designed for an output of 40,000 kVA, 3-phase, 50 cycles and are of the core type with natural cooling. The voltage ratio at no load is 13.8/150 kV, and off-load tappings are provided controlled by a manually and externally operated off-circuit tap changing switch. The transformers have radiators fitted round the tanks and at right angles to them. Fig. 12 shows one of the main transformers during installation at the switching station.

The tanks are fabricated from mild steel plate strongly reinforced to permit handling when filled with oil. The yokes are clamped by fabricated steel frames at top and bottom and the legs are secured by a single row of bolts from which the pressure is distributed over the face of the limbs by a series of short steel pads ; both bolts and pads are insulated from each other and from the core. Each completely erected unit comprising core and windings was dried out in a vacuum tank and impregnated with hot transformer oil.

The tappings are taken from the centre of the H.V. coil stack, and tap changing is effected, with

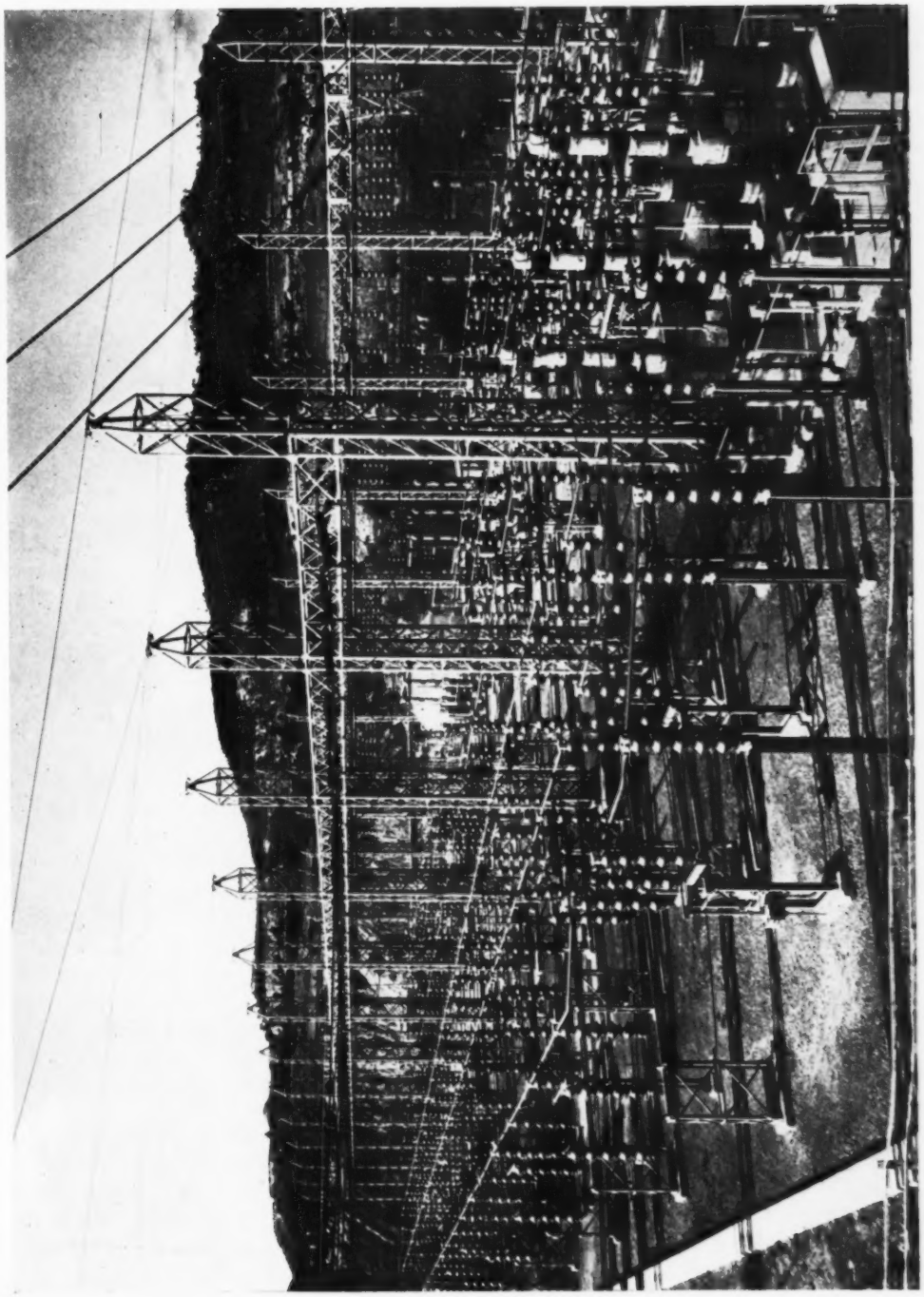


Fig. 13. *The* 150 *kV switching station at Cofrentes, with bus-coupler air-blast circuit-breaker in foreground*

the transformer off circuit, by means of a change switch operated by a hand wheel on the tank cover. The switch is arranged in tiers to operate all three phases simultaneously.

Other fittings include an expansion vessel, double-float Buchholz relay, dial type oil thermometer and winding temperature indicator.

To supply the station auxiliaries, three unit transformers are provided each giving 2,000 kVA, 3-phase, 50 cycles, with a ratio of 13.8/12.3 kV. They are of the outdoor type with natural cooling through radiators, their general mechanical construction being similar to that of the main step-up transformers. On-load tap-changing equipment is provided on the H.V. winding and is housed in a steel tank bolted to the side of the transformer tank. Tap changing is remotely controlled by push-button and operates on the mid-point auto-transformer scheme in which the number of tappings obtainable is double that taken from the main transformer winding, intermediate tappings being taken from the mid-point of the auto-transformer which is fully rated and capable of continuous operation even if a tap-change operation is not completed.

For connection between the auxiliary alternator and the 12.3 kV unit transformer busbars there are two 500 kVA auxiliary transformers of the core type, oil immersed with natural cooling, with a no-load ratio of 12.3 kV/220 volts.

Switchgear

Referring to Figs. 3 and 4, showing diagrammatically the 150 kV Madrid-Millares electrical system and the connections at Cofrentes, in addition to the outdoor switching station and all the indoor switchgear at Cofrentes, The English Electric Company also supplied the switchgear for the outdoor switching station at El Picazo with its control gear, the outdoor substation at Olmedilla and the 150 kV circuit breakers and air compressors for use at Millares, Cortes and Villora power stations and at Villaverde substation. Thus the Company has supplied the whole of the 150 kV circuit breakers for the Madrid-Millares system, 34 in number, and all are of the air-blast type, having three interrupters in series per phase, with a breaking capacity of 2,500 MVA.

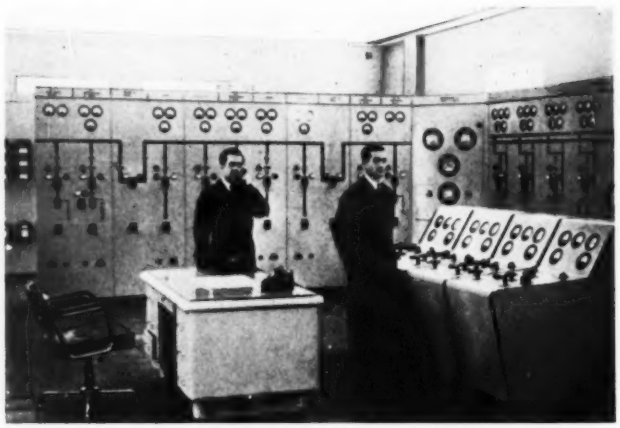


Fig. 14. *Control room at Cofrentes power station*

At the Cofrentes outdoor switching station (Fig. 13) the 150 kV overhead gear is mounted upon galvanised steel structures. Duplicate busbars are provided and there are equipments for three transformers, eight feeders and one bus-coupler. There are two duplicate compressors for the air-blast circuit-breakers, and a transformer oil handling plant.

Indoors at Cofrentes power station are the generator control desks and the control and relay boards for the 150 kV and 12.3 kV switchgear (Fig. 14), the 12.3 kV oil-break cubicle type switchgear, 220 volts unit and common service switchboard, battery board, 13.8 kV generator isolators and neutral earthing equipment.

From the diagram in Fig. 4 it will be seen that the unit transformer system has been adopted for supplying the station and unit auxiliaries, and that provision has been made for maintaining their supply from other sources. For normal operation each main generator is coupled direct to the 150 kV busbars through its own main transformer, but provision is made by means of the 13.8 kV isolators for a supply from the 150 kV busbars to the unit transformers if the main sets are shut down. There is also the 500 kVA auxiliary turbine-driven set acting as a further alternative supply to the 220 volts busbars.

All 150 kV feeder breakers are equipped with auto-reclose mechanism which operates in conjunction with the carrier current contra-phase protection installed throughout the system, except on the Olmedilla-El Picazo and Madrid-Villaverde sections where pilot wire protection is employed at lower cost, this being permissible on account of the short distances involved.

The English Electric Company's network analyser was of much service in providing an extensive system analysis for Hidro-Electrica Espanola. The study of such an analysis enables the flow of power and reactive kVA, and the voltage regulation, at selected points in the system to be predicted under varying load and fault conditions. In the Madrid-Millares system power may flow at different times in any one of three ways ; (1) Millares to Madrid (2) Madrid to Millares (3) Cofrentes to Madrid and Cofrentes to Millares. With a line some 200 miles long it was essential to determine the synchronous plant necessary for a workable system and where it should be installed. At Cofrentes one set at a time can be run as a synchronous condenser.

Commissioning

No. 1 generating set at Cofrentes was put into service on load, feeding Madrid via Olmedilla substation, on 18th October 1951, after a very successful series of tests. Water was available at 9.30 a.m. and by 5.20 p.m. the set was delivering 25 MW to Olmedilla. At 11.30 p.m. load rejection tests were commenced and these showed satisfactory speed regulation results culminating in the rejection of 40 MW at 12.10 a.m. The second set was put on commercial load in June 1952, and the third set in March 1953.

Acknowledgments

Grateful acknowledgment is made to Mr. H. S. Pound-Corner, formerly technical representative of The English Electric Company in Madrid, and to Mr. R. L. Brown of Export Department, Stafford, for much of the general information regarding the scheme described.

Water Turbine Governors

By N. G. DENNIS, M.A., D.I.C., A.M.I.C.E., A.M.I.Mech.E., A.M.I.E.E.,
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This article is in all essentials an abbreviated reproduction of the paper presented by the author at the General Meeting of the Institution of Mechanical Engineers on the 7th November 1952, with some additions from his articles published in 'Water Power' from February to May 1953.

PART I

THE ADVENT OF large-scale electrical transmission of energy brought a new era to water turbines and their control mechanisms. Nevertheless, the modern governor remains the same as far as the principle of its control of prime mover speed is concerned, and this is shown in Fig. 1. In principle it is seen that if the speed of the turbine is not at its desired value, the centrifugal device of this simple governor operates to correct the speed.

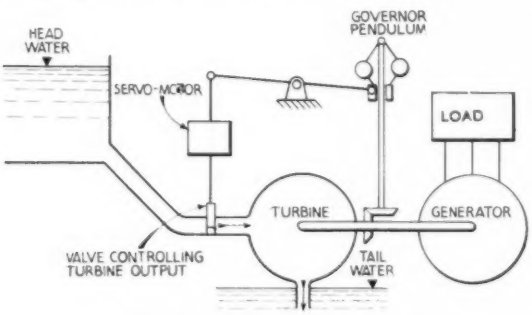

Fig. 1. Rudimentary governor

Since the early days of hydro-electric power, engineers all over the world have had to overcome numerous problems caused by the much larger power plants and the necessary improved quality of control of speed and power. The designer to-day has to consider intricate control problems with careful regard to many factors such as the maximum rate of action which is possible with stability.

The governing of a water turbine is, in a broad sense, similar to that of any other prime mover. However, there are two special difficulties which have to be overcome. The first is the high inertia and incompressibility of the working fluid, and the second is the heavy regulating mechanism which has to be operated. This heavy mechanism results from the large operating force required, and naturally there is a certain amount of friction. When the guide vanes move, the inertia of the water causes changes in pressure at the turbine which act contrary to the guide vane movement in their effect on the speed and load of the turbine; to counteract this effect and avoid 'hunting,' special stabilising devices have to be included in the governor. Fast movements of the heavy regulating mechanism mean that a high degree of amplification in the control mechanism is required, and the operating servomotors are often very powerful.

Principles of Operation

Fig. 2, which applies to any water-turbine governor, shows the four different fundamental movements which, added together, actuate the distributing valve and servomotor which control

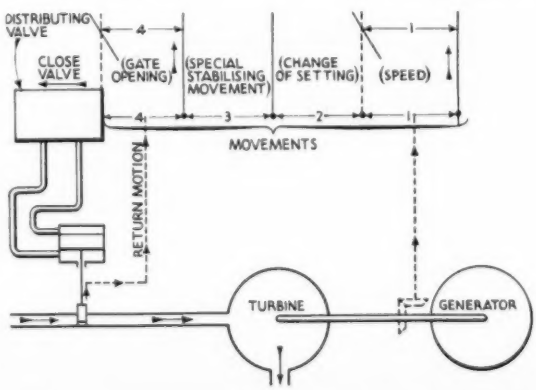

Fig. 2. Movements added at main distributing valve

* *Formerly Chief Hydraulic Research Engineer.*

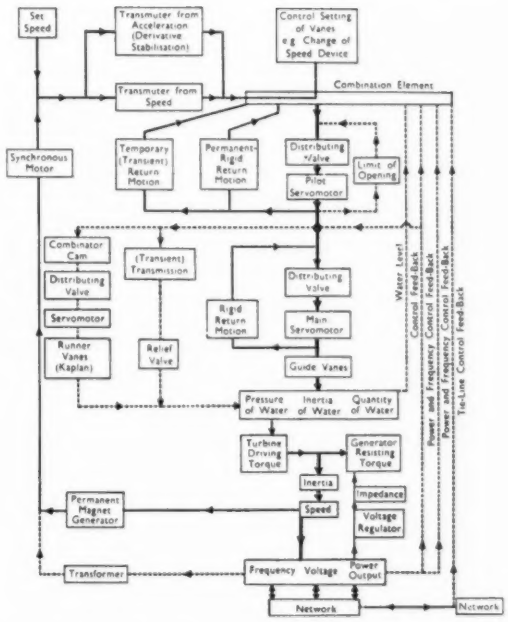

Fig. 3. Block scheme for control of a reaction turbine (turbine on load and under full automatic governor control)

the gate apparatus. Any deviation of the regulated quantities (speed or load) causes a change of movement 1 or movement 4 which actuates the distributing valve and the main valve to correct the deviation. Steady combinations of movements 1 and 4 constitute the speed-load droop. Without movement 3 the system would hunt, that is, be unstable. Movement 2 is the familiar ' change of speed ' device which becomes primarily a ' change in load ' device when the unit is connected to a network. This changes the datum combination level of the speed-load relation. An example of a modern governor is given later in this article ; this should be considered in conjunction with Fig. 2.

Fig. 3 shows a much more comprehensive block scheme covering the governor system for a water turbine. It also shows a very small part of the generator and network controls[1]. This diagram specifically refers to a reaction turbine, but with a few modifications it can apply to an impulse turbine.

Unlike most other prime movers, it is found that special stabilising elements must be included in the control of a water turbine to avoid hunting, and this can be done by either of two methods : transient feed-back stabilisation (temporary-return motion) or derivative stabilisation (the addition of an element sensitive to angular acceleration).

The operation of the other possible feed-backs for tie-line, frequency and water-level control is discussed later. The only feed-backs which can operate simultaneously are those which are part of the same major-control loop, or feed-backs from inter-related variables, probably with very different time constants such as gate opening and water level. Simultaneous operation of feed-backs allows the turbine gate opening to be simultaneously influenced by speed, frequency, water level, etc., but the basic control equation fed into the governor should not have more than one degree of freedom.

To achieve the high performance and stability of modern governors, frictional effects have to be

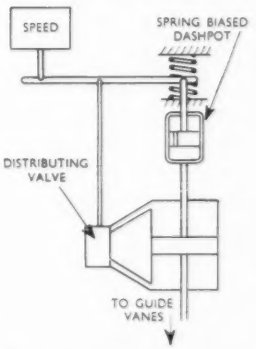

Fig. 4. Temporary-return-motion governor

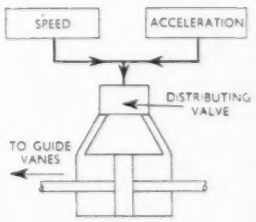

Fig. 5. Accelerometer governor

reduced to a minimum, the rigidity of connecting linkages has to be carefully considered, and backlash at certain joints has to be avoided by arranging for a unidirectional force across the joint.

It is desirable to use a governor of as great rapidity of action as possible for a hydro-plant, so that it can follow load changes quickly and ease conditions on the electrical power network. The rapidity of action cannot exceed a certain value which is fixed by stability considerations—as in

1 *The method of starting and stopping the turbine is given in a similar diagram by A. C. H. Frost and W. Brittlebank in ' The control of hydro-electric plant.' Proc. I.E.E.* (1951), *pt.* 1, *vol.* 98, *p.* 129, *Fig.* 6.

other closed-sequence control systems where amplification is restricted by stability. The rate of governor action for large regulating movements is usually determined in practice by the maximum permissible speed and pressure variations which follow large load changes. In this case the amount of variation permissible is decided from experience.

Different Types of Governor

Accelerometer and Temporary-return Motion.—Fig. 4 shows a simple diagram of a temporary-return-motion governor, and Fig. 5 shows an accelerometer governor.

Although external responses are similar, the

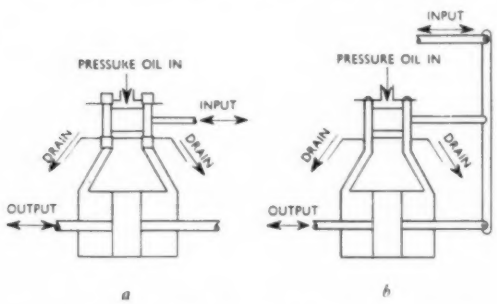

Fig. 6. Uses of distributing valve and servomotor

a Integrating servomotor with forces amplified
b Displacement transmission with force amplification

internal behaviour of each alternative is very different. Especially, the relation between the distributing-valve and the servomotor movements is different. With the accelerometer arrangement, there is no return motion (feed-back) from the servomotor to the distributing valve (Fig. 6a). The movement of the servomotor integrates the movement of the distributing valve as a function of time, and it is therefore called an integrating servomotor. The distributing valve and the servomotor of the temporary-return-motion governor are linked by the temporary-return-motion, and this causes, to some extent, the servomotor to follow proportionally the movement of the distributing valve (Fig. 6b). In practice, it is found that the distributing-valve piston of the accelerometer soon reaches a big displacement during a change of speed, whereas that of the temporary-return-motion governor moves comparatively little ; however, this is counterbalanced by the fact that the servomotor of the accelerometer must have a slow rate of response for stability, whereas the servomotor of the temporary-return-motion governor acts practically instantaneously. The overall behaviour is thus the same, since each governor can be considered as composed of two elements, one slow and the other fast.

The two methods of stabilisation of the speed control have a very similar total effect. The accelerometer governor will be seen to add acceleration and speed changes, integrate the sum, and cause this to act on the guide vanes. The temporary-return-motion governor obtains the effects of both speed and the integrated speed by means of the action of the return-motion dashpot. Fig. 18b shows that when the orifice of the dashpot is closed the return motion is rigid, and, with the servomotor, forms a direct transmission of displacement. On the other hand, if the orifice is large, there is no effective return motion, and the servomotor forms an integrative element. Thus, when the orifice forms a partial restriction, combined transmission and integration takes place. Therefore both types of control cause the guide-vane movement to be influenced by both the speed and integrated speed. Fig. 7 is a schematic comparison of the two types of control. It is the influence of the integrated speed on shaft displacement which confers isochronous control when required.

It is obviously not true to say that the accelero-

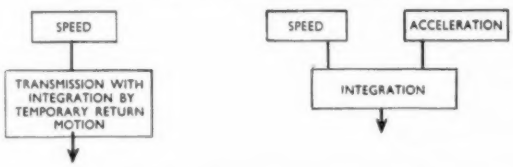

Fig. 7. Comparison of two existing types of governor

meter immediately responds to acceleration before any change of speed has taken place, whereas a temporary-return-motion governor operates only from the speed and, furthermore, is restrained by its return motions. Many analyses have shown both to be very similar in action.

In general, a servo-system with derivative stabilisation is less resistant to output disturbances than is a system stabilised by feed-back. In this

specific instance, any friction and backlash in the operating gear of the guide vanes have a worse effect with the accelerometer than with the temporary-return-motion governor. This difference in effect is reduced if the integrating servomotor of the accelerometer is not the last servomotor of the sequence, and does not have to operate directly against static friction ; otherwise, integration takes place under bad conditions, which will cause hunting.

With a temporary-return-motion governor, the rate of action can be made as rapid as desired since it is controlled by the temporary-return motion itself. This makes adjustment of the governor at site very easy—especially since changes in the stroke of the temporary-return motion itself are usually not needed, and adjustment is required simply on an orifice which controls the characteristic time of the dashpot. Similar adjustments on an accelerometer governor are either more difficult or utilise a complicated mechanism, since both the amount of acceleration injected and the rate of response of the integrating servomotor have to be adjusted.

Electric Governor.—The intensive development of hydro-mechanical governors over the last half century has resulted in a high degree of performance, reliability and cheapness ; furthermore, maintenance is comparatively easy.

However, certain advantages are likely to be gained by the more extensive use of electrical circuits on the low-power side of the governor-control system. Theoretically these hold possibilities of greater ease and flexibility in regard to both the quantities which are controlled and the manner in which the control can be stabilised. For instance, the transmutation and remote transmission of distant water level or the gate opening of a distant turbine, and any desired combination of these, would appear to be made simpler; furthermore, standard electrical stabilising networks promise immediate application to such control circuits[2].

Possible New Types of Governor Control.—When hydraulic conditions are fixed, the maximum rate of governor operation and the moment of inertia of rotation are mutually related in a manner partly depending on the type of governor ; for example, *Condition* (2) in the ' Simple Governor Theory ' (in Part II) where the coefficient 3.74 applies to either a temporary-return-motion or accelerometer governor. For a certain rate of governor operation there is a minimum inertia, and for a certain inertia there is a maximum rate of governor operation. Consideration has been given recently as to whether these conditions can be relaxed. New types of governor have been examined, in this light, and also to see if network regulation as a whole can be further improved. The types of control outlined below have definite possibilities for special hydro-electric stations.

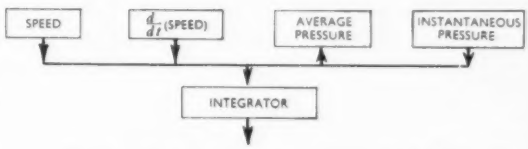

Fig. 8. *Stabilisation by pressure feed-back*

Fig. 8 shows a feed-back from the momentary pressure in the pipe-line. Fig. 9a shows the addition to an accelerometer governor of an element responsive to the rate of acceleration. Both these involve serious practical difficulties. Fig. 9b shows a simplification of Fig. 9a, and has the same effect. Fig. 10 shows a combination of temporary-return-motion and acceleration governors, the temporary-return-motion action being represented by combined transmission and integration.

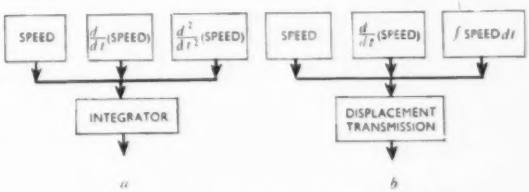

Fig. 9. *Double derivative stabilisation*

a Addition to accelerometer governor of an element responsive to the rate of acceleration

b Simplified form of a

Theoretically these methods can give an improvement of up to six times the rate of governor operation for a given inertia. The arrangement in Fig. 10 gives the least improvement[3].

2 *Further information on this subject is given by E. Brodersen and S. E. Hedstrom in ' Electro-hydraulic regulation of water turbines,' 1950 Conference Internationale des Grandes Resaux Electriques a Haute Tension (Cigre), and by M. Cuenod in ' Un regleur electrique de vitesse', La Huile Blanche* (1950) *vol. 5, p.* 123.

3 *These methods are described in more detail by P. Almeras in ' Procédés d'amelioration des qualities de reglage des groupes hydro-electrique,' Societé Hydro Technique De France* (1949), *and by A. Dejou in ' Considerations sur les regulateurs des groupes generateurs hydro-electrique des basse chute,' Revue Générale d'Electricité* (August, 1948).

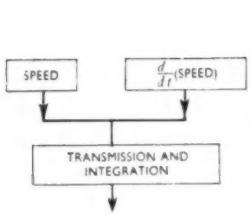

Fig. 10. *Combination of two existing types of governor*

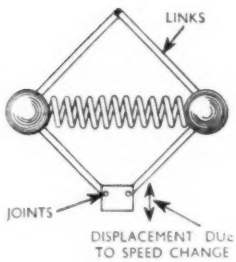

Fig. 11. *Typical obsolete pendulum*

Operating-elements in Hydro-mechanical Governors

Centrifugal Devices.—These centrifugal devices act as transmuters from shaft speed to mechanical displacement.

In the past there was a great variety of designs ; a typical example is shown in Fig. 11. These old designs have developed comparatively recently into two main types, shown in Figs. 12 and 13. In both of these, backlash is eliminated and the only friction present is a very slight hysteresis in the springs.

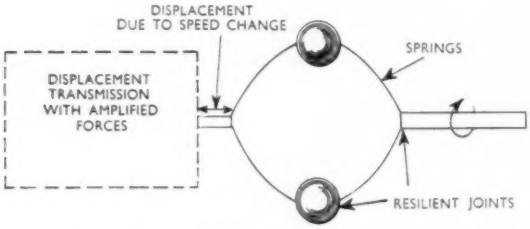

Fig. 12. *Modern version of pendulum*

With the type shown in Fig. 13, the transmutation really ends at the inclined face of the whirling mass, after which there is an incorporated displacement transmission. This displacement transmission will easily be seen to be a pilot relay as described later (Fig. 15a).

Centrifugal Device Drive.—There are three types of transmission of speed between the turbine shaft and the centrifugal device. These are given below in order of convenience and elegance of station layout.

(1) *Electric Drive.*—Invariably a synchronous induction motor is used, and this may be fed with alternating current in one of three ways, given in order of popularity :—

(i) permanent magnet generator mounted on main shaft ;

(ii) special windings in the pilot exciter if present, which is also equipped with slip-rings ;

(iii) special transformer at the generator terminals.

Both methods (i) and (ii) are generally approved, but they are bulky and inconvenient in the comparatively unusual case of a very slow-speed

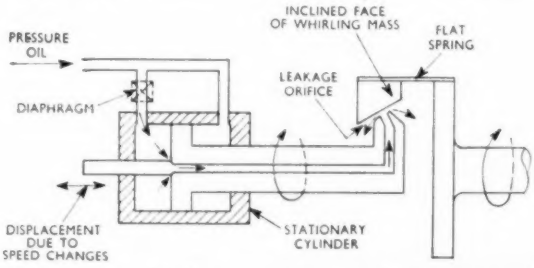

Fig. 13. *Modern pendulum with incorporated displacement transmission*

Kaplan turbine. Method (iii) is prone to interference from faults on the electrical network. Method (i) gives the quickest follow-up of the centrifugal device when the turbine is being started up. In all methods time lag of transmission must not be too large, otherwise hunting will result.

(2) *Mechanical Drive.*—Mechanical drive is very reliable. Extreme rigidity of transmission must be avoided, particularly when accelerometer governors are used, since comparatively high-frequency oscillations of the turbine shaft—due to electrical or hydraulic causes—can induce severe hunting.

(3) *Friction Drive* (*Belt or Friction Wheel*).—Friction drive is more popular in some countries

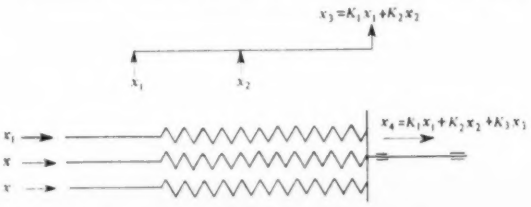

Fig. 14. *Addition of displacements*

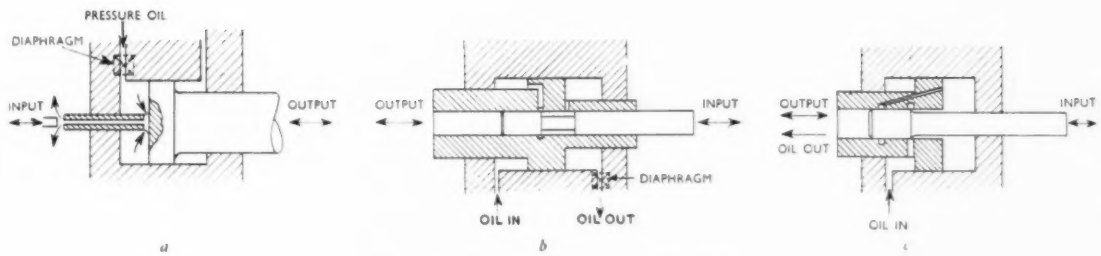

Fig. 15. Types of hydraulic pilot relay

than in others. It is certainly cheap, but is prone to jerky running unless carefully fitted. Jointless silk belts have been used, but necessitate overhung pulleys. If belt drive is used, devices must be added which shut down the turbine in the event of belt failure.

Addition and Subtraction.—This is performed at the combination element as shown in Fig. 3. The two most usual ways of adding (or subtracting) linear displacements are shown in Fig. 14 which is self-explanatory and shows the methods of the ' floating lever ' and ' parallel springs.' The addition (or subtraction) of angular displacements is made by differential gearing or torsion springs, both of which correspond to the methods shown in Fig. 14. Mechanical movements can often be conveniently added when they are a mixture of linear and angular displacements, and screw threads then become useful.

Combination of movements by means of springs is generally used when the number of angular or linear quantities to be added exceeds two, and the use of combinations of the balanced lever would be somewhat awkward. Furthermore, a ' balanced three-dimensional body ' which may involve six quantities becomes too complicated.

Hydraulic Pilot Relays.—Fig. 15 shows three types of pilot relay in use. They provide a 1/1 transmission of displacement with great amplification of control force and, in consequence, a great reduction in error due to output disturbances. With the relays in Fig. 15, in each case the hydraulic forces on both sides of the piston balance under steady-state conditions. The pressure on the side of the piston with the larger area has therefore to be less than the full pressure on the other side ; this reduction of pressure is easily achieved by placing a diaphragm at entry and some kind of controlling restriction at exit. The controlling restriction can be either a choked nozzle, or a steering edge similar to a distributing valve. The input movement operates the controlling restriction to cause the piston (output element) to follow it.

Divided Pilot Relay.—This relay (Fig. 16) can provide easy amplification of stroke, in addition to force, as required. The return motion from a single-acting servomotor acts by means of a simple linkage to move the sleeve of the control valve.

Distributing Valves and Servomotors.—A simple distributing valve with a double-acting servomotor is shown in Fig. 6a, whereas Fig. 17 shows a single-acting arrangement where the smaller side of the piston is always under the same oil-pressure (or spring-loading). Where very heavy operating forces are required, double-acting servomotors are used because for the same dimensions of cylinder

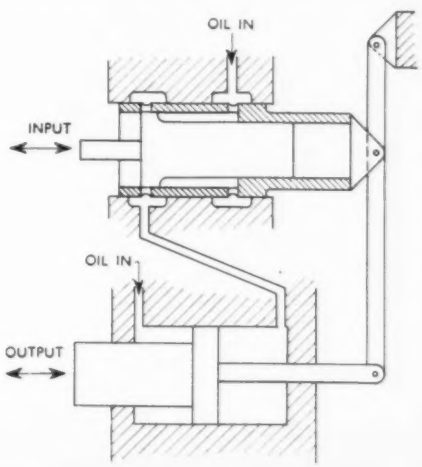

Fig. 16. Divided hydraulic relay

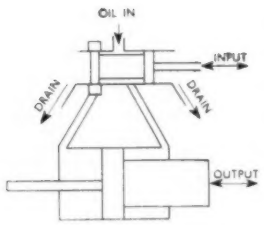

Fig. 17.
Single-acting servomotor

and the same available oil pressure, the force available is double that of the single-acting arrangement.

Distributing valves are often built integrally with hydraulic relays, in which case the piston of the distributing valve is in one piece with its pilot servomotor. Also a pressure-sensitive control is achieved by adding a piston-spring element to one end of the valve.

Axial friction in distributing valves and servomotors can, if necessary, be dealt with by causing either the piston or the cylinder to rotate. There is a slight frictional effect which is dependent on axial velocity, but it is negligible.

Friction in distributing valves is sometimes overcome by the introduction of a ' dither ' into the system. In water-turbine governors, care must

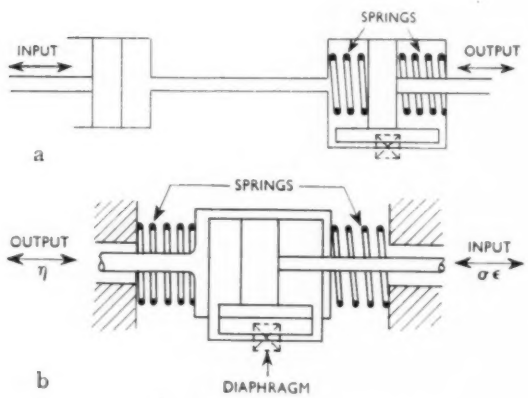

Fig. 18. *Temporary transient transmission*

a Either piston or cylinder can be fixed as convenient

be taken to localise this ' dither ' and ensure that it does not reach the main servomotors ; otherwise there is a danger of hunting in conjunction with water-hammer in the main conduits, and excessive wear on the turbine regulating gear.

The lap employed in the design of a distributing valve depends on its function. In this connection there are the opposed requirements of minimum leakage and maximum sensitivity. A simple positive overlap will give minimum leakage, but a small ' dead ' band of control. The latter can be avoided by the suitable use of a slight negative lap, or by suitable grooving of the steering edges, which is equivalent.

For a given rate of operation of a servomotor against certain fixed conditions of resisting force to its movement, there is an economic size of servomotor and distributing valve. To illustrate this, in Fig. 6a assume that there is a resisting force P, of constant value. Clearly, the servomotor must be of at least a certain area to enable it to move at all. If the servomotor size is only just above this critical value, a very large distributing valve will be needed because of the very small difference between the working pressure and the ' resisting pressure ' available to drive the oil through the distributing valve. On the other hand, if the servomotor is very large, the ' resisting pressure ' will be very low, but the large flow of oil required will again result in a big distributing valve. An economic compromise between these two extremes has to be reached, and, at the same time, the safety factor of operation must be sufficient.

Temporary-return-motion System.—The usual mechanism for a temporary-return-motion system is a dashpot spring combination, which can be adapted either for hydraulic or mechanical transmission of displacement feed-back from the output element as shown in Fig. 18.

The ' rigidity ' of the transmission is controlled by the size of the effective orifice of the dashpot. This rigidity is arranged to vary as a function of the displacement of the dashpot by means of specially cut orifices in the walls of the dashpot piston or cylinder, which are opened or closed according to the relative position of the two. In water-turbine governors, the rigidity is always made considerable for small displacements and less for larger displacements ; this is to reduce the restraining action of the feed-back when large disturbances occur. Similar arrangements are made on accelerometer governors.

Limit of Opening Device.—The limit of the opening device is shown in Fig. 19 and prevents the distributing valve from opening the servomotor

beyond a certain value. Apart from this, operation of the system is not affected. In Fig. 19 the lever of the limit of opening device sometimes actuates an exhaust valve which releases pressure from the opening side of the servomotor. The device is often used for controlling the turbine load when frequency is very low.

Accelerometer Systems.—Accelerometer systems can be divided into three types.

In the first type, shown in Fig. 20, transmutation

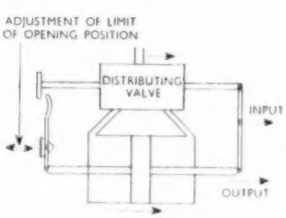

Fig. 19. Limit of opening device

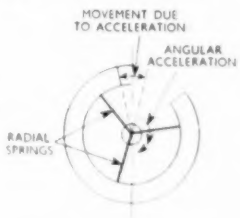

Fig. 20. Transmuter from acceleration

from angular acceleration to displacement takes place. This is achieved by a mass mounted by springs on the shaft and, when angular acceleration of the shaft occurs, there is relative movement between the mass and the shaft. A pilot relay similar to that shown in Fig. 13 is usually incorporated.

The second type utilises the change of pressure in a spirally-wound pipe filled with mercury, or a viscous oil pump with spiral channels.

The third type utilises a hydraulic phase-advancer which differentiates the velocity input to it. This is shown in Fig. 21.

Double Regulation Systems.—The following constitute double regulation systems of a water turbine :—

(*a*) *Guide Vanes and Runner Vanes with a Kaplan Turbine.*

Under steady-state conditions, the condition of best efficiency for any operating load requires that there be a certain definite combination of guide vane and runner vane angles.

Although other arrangements have been suggested[4], the usual method is to operate the guide vanes in the normal fashion, and to control the runner vanes by means of a separate control system actuated from a cam positioned according to the guide-vane movement. This special control system usually acts through a pilot relay followed by a displacement-transmission system, as in Fig. 6b. With the latter, oil has to be led to and away from the rotating servomotor.

(*b*) *Guide Vanes and a Relief Valve on a Reaction Turbine.*—The purpose of the relief valve is to reduce the rise in water pressure which occurs with a pipe-line when the turbine undergoes a major rapid-closure. The guide vanes are controlled in the usual manner, and the relief valve operation is actuated by the guide-vane movement. This is done by means of one of the temporary transmission systems (Fig. 18). This temporary transmission differs from the case previously mentioned in that the displacement occurs in only one direction from the position of rest.

(*c*) *Spear and Diffuser Operation for Pelton Turbines.*—On account of water-hammer in con-

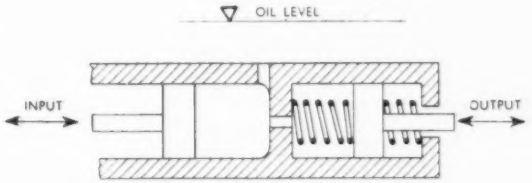

Fig. 21. Hydraulic phase-advance mechanism

duits, the spear of a Pelton turbine which controls the flow can move only slowly. By itself, it would cause unacceptable speed rises on rejection of load and, to avoid this, some kind of temporary flow diversion arrangement is added. The first of these devices that will be described is the diffuser.

Under steady-state conditions, the ends of the diffuser blades (Fig. 22a) are retracted into the spear and the two form a continuous and smooth surface. When the turbine has to reject load suddenly, the diffuser very quickly shoots forward into the flow in the nozzle (Fig. 22b), and diverts it from the buckets of the Pelton runner. The spear slowly follows the diffuser and reduces the flow of water at the rate determined by the hydro-dynamic and mechanical conditions. The combination of

4 *See G. Fabritz* (1940). '*Die regelung der kraftmaschinen*' (*J. Springer, Berlin*).

spear and diffuser then settles down to a new steady position[5].

The transient diversion action of the diffuser is the result of the inclination of the diffuser blades. This causes the solid jet to break up, to the desired extent, into a hollow-vortex cone.

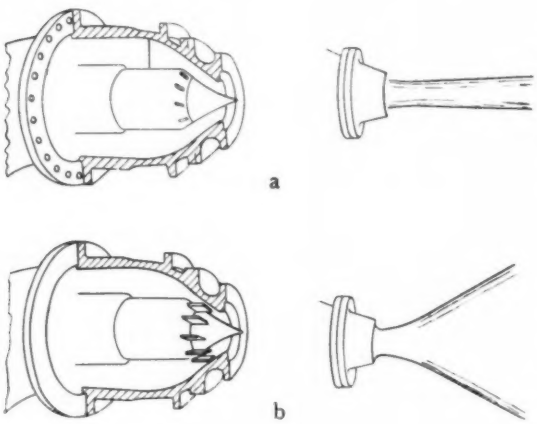

Fig. 22. Spear, diffusing blades, and jet

a Normal position under steady load with solid jet

b Diffuser in acting position and hollow jet

Details of the method of hydraulic control will not be described here, since the control system is a special development of the pilot nozzle shown in Fig. 15a, where the diffuser forms the input element and the spear the output element. The control is characterised by an immediate follow-up of the spear for small movements of the diffuser; however, this quick response of the pilot nozzle, which ensures good stability, very quickly reaches saturation for larger movements of the diffuser, and the spear then moves at its maximum velocity as determined by the pipe-line.

(*d*) *Spear and Deflector Operation of a Pelton Turbine.*—The deflector is an alternative device to the diffuser, and is shown in Fig. 23. The deflector must be arranged almost to touch the jet, whatever its size, under steady-state conditions. When a rapid drop in the electrical load occurs, the deflector swings across the path of the jet and diverts a certain amount of it from the runner buckets. As the spear slowly reaches its new steady-state position, so the deflector gradually swings out of the jet.

Pressure Oil Supply to Governor.—The consumption of oil varies greatly. If the turbine is running under steady conditions, only the small quantity necessary to supply the leakages through the operating clearances of the mechanisms will be required. However, when changes of load occur, a much greater quantity of oil is used—chiefly to operate the main servomotors.

With small turbines, usually a single oil-pump is kept continuously running. When not supplying oil to the governor, it discharges back into the sump through a spring-loaded valve. An alternative is to use a two-pump arrangement, in which the small pump supplies the continuous basic leakage and the big pump idles, except when the load change—and hence the distributing-valve movement—is more than a certain amount, when an oil relay switches its supply to the governor. No pressure receiver is used in either case.

With large turbines, where a single stroke of the main servomotor may involve more than 300,000 ft-lb of energy in a few seconds, economy dictates that the pump supplies an air pressure vessel which acts as a pressure receiver.

The maintenance of the correct level of oil in this receiver constitutes a problem of its own, which can be solved either manually or automatically. Three methods can be used for the supply of air to the receiver :—

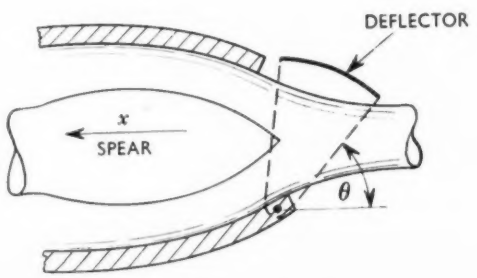

Fig. 23. Pelton nozzle with deflector

5 *Further information is given by P. W. Seewer in 'Recent developments in hydro-electric engineering.' Proc. I.Mech.E.* (1936), *Vol.* 134, *p.* 283.

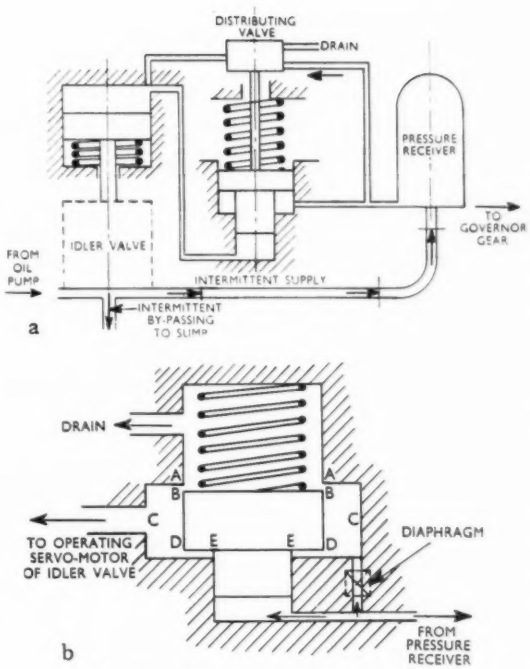

Fig. 24. Idler valve control system

a Separate feed-back b Integral feed-back

(1) supply from a separate air compressor ;

(2) supply by air admission into the oil stream on the suction side of the pump ;

(3) a supply which utilises an oil level as the piston of a reciprocating pump. This oil level reciprocates up and down in a separate vertical chamber adjacent to the pressure receiver[4].

Idler Valve.—The idler valve is sometimes known as a ' change-over valve ' or a ' by-pass valve.' Its functions are to economise on the energy consumption and wear of the main governor oil-pump and to minimise the heating of the oil.

A typical case is where the idler valve controls the pressure in the pressure receiver between 270 and 300 lb per sq. in. While the pressure is falling between these two limits, the idler valve diverts the flow from the main pump back to the oil sump with no appreciable waste of energy. As soon as the pressure reaches 270 lb per sq. in. the idler valve operates to connect the pump to the pressure receiver ; when the pressure has reached 300 lb per sq. in., the idler valve diverts the flow to the sump.

In addition to the change-over action just described, the valve can also be designed as a safety valve, although, for absolute security, separate safety valves are usually provided.

Fig. 24a shows a device for obtaining the change-over action. This employs a feed-back from the idler-valve operating piston. The limits of pressure are determined by the relative magnitude of the two hydraulic forces acting on the spring-loaded pilot servomotor.

A neat method which utilises the simple piston spring arrangement is shown in Fig. 24b[6]. The operation of this is essentially by the edges AA and BB which control the escape of oil in chamber C, and hence whether or not oil pressure is applied to the annular area DE. This device is similar to the arrangement shown in Fig. 24a, except that the physical arrangement of the distributing valve and pilot servomotor is simpler.

A second way of obtaining the same result is shown in principle in Fig. 25. The central spindle

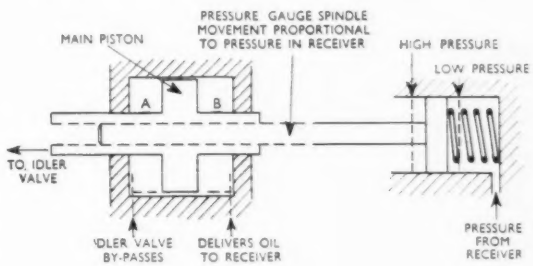

Fig. 25. Alternative method of operation of idler valve

is operated by a servomotor and spring combination. It is so arranged that its position depends only on the oil pressure in the pressure receiver, and it is, in effect, a pressure gauge. This pressure-gauge spindle is virtually surrounded by the separately operating piston of the idler valve. It is not proposed here to enter into further details [4 6], but oil passages can be arranged between the pressure-gauge spindle and main piston to

6 *See A. Ribaux* (1947). ' *Régulateurs de vitesse* ' (*Editions La Moraine, Geneva*).

control the latter in the desired way. When the pressure-gauge piston reaches the desired top limit of pressure, it will be located in its extreme left-hand position. It then suddenly causes the oil pressure in chamber B to build up, and the pressure in chamber A to diminish. The main piston then suddenly moves through its full stroke to its extreme left-hand position. A similar action takes place when the lowest desired pressure in the receiver is attained.

Miscellaneous Features on a Governor.—Automatic air valves are often installed for transient-air admission into the draft tube, when required for closing movements of the turbine. Steady-state air injection is advantageous with certain types of Francis runner at part load, since it eliminates vortex pulsations underneath the runner ; these pulsations are not due to cavitation and are of a much lower frequency.

An oil relay is usually provided, which acts as a ' master ' emergency shut-down device. Many different protection arrangements on both the electrical and hydraulic apparatus of the power plant focus on this relay, and any one of them can cause the governor to shut down.

If required, the guide-vane operating mechanism can be locked automatically when the vanes are in the fully-closed position.

This article will be concluded in Part II to be published in the September 1953 *issue of this journal, Volume* 13 *No.* 3.